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AN INVESTIGATION OF THE EFFECT OF
AUTO-THROTTLE DEVICES ON AIRCRAFT CONTROL
IN THE CARRIER LANDING APPROACH

GERALD R. BELL

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Gerald R. Bell

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IN THE CARRIER LANDING APPROACH**

by

Gerald R. Bell

Lieutenant Commander, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

**MASTER OF SCIENCE
IN
AERONAUTICAL ENGINEERING**

**United States Naval Postgraduate School
Monterey, California**

1963

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ABSTRACT

An automatic-throttle compensation system has the capability of removing the problem of aircraft speed instability in the carrier landing approach. Various systems have been proposed and tested, each differing in input sensed variables. Two representative systems are investigated analytically and by the use of digital programmed Nyquist plots and analog simulations. An attempt is made to determine optimum gain constants by using various forcing functions in the analog simulation. Comparisons of the responses of the two systems are made using time history analog records. A digital computer stability program, applicable to any aircraft, is included.

The writer wishes to express his appreciation for the assistance and encouragement given him by Professor E. J. Andrews of the U. S. Naval Postgraduate School. Gratitude is also due Ling-Temco-Vought Incorporated, Specialties Incorporated and Bell Aerosystems for providing the necessary data used in the investigation. In particular, the author wishes to thank the Stability and Control Section, Airframe Design Division, of the Bureau of Naval Weapons for the valuable assistance supplied in the form of pertinent technical reports.

TABLE OF CONTENTS

Section	Title	Page
	Table of Symbols	viii
1.	Introduction	1
2.	Discussion	3
3.	Artificial Speed Stability Through Automatic-Throttle Techniques	8
4.	Experimental Methods and Results	14
5.	Conclusions	25
	Bibliography	66
Appendix I	Derivation of Transfer Functions	67
Appendix II	Dynamic Stability Fortran Program	72
Appendix III	System Mechanization for the Analog Computer	89

LIST OF ILLUSTRATIONS

Table		Page
I.	Computed F-8 Airplane Stability Derivatives and Associated Aircraft Parameters	27
II.	Sample Printout, Fortran Stability Program, LONGSTAB	29
Figure		
1.	Thrust Required Versus Airspeed	30
2.	C_L Versus L/D, F-8 Airplane	31
3.	Block Diagram, System 1 Auto-Throttle, with Transfer Functions	32
4.	Block Diagram, System 2 Auto-Throttle and Engine, with Transfer Functions	33
5.	Nyquist Diagram of System 2 Auto-Throttle Open Loop Transfer Function	35
6.	Composite Block Diagram of Complete Automatic Throttle-Airframe System	36
7.	Angular Definitions and Signs	37
8.	Photograph of Analog Setup	38
9.	Photograph of Analog Setup	39
10.	Time History, 1.3° Up Elevator Deflection Input, System 1-a	40
11.	Time History, 1.3° Up Elevator Deflection Input, System 1-b	41
12.	Time History, 1.3° Up Elevator Deflection Input, System 2	42
13.	Time History, 5 Knots Horizontal Gust Input, System 1-a	43
14.	Time History, 5 Knots Horizontal Gust Input, System 1-b	44

15.	Time History, 5 Knots Horizontal Gust Input, System 2	45
16.	Time History, 4° Step Input Pitch Angle, θ , System 1-a	46
17.	Time History, 4° Step Input Pitch Angle, θ , System 1-b	47
18.	Time History, 4° Step Input Pitch Angle, θ , System 2	48
19.	Time History, 4° Step Input Pitch Angle, θ , Basic Airframe	49
20.	Time History, .02 cps. Triangular 1.32° Elevator Deflection Input, System 1-a	50
21.	Time History, .02 cps. Triangular 1.32° Elevator Deflection Input, System 1-b	51
22.	Time History, .02 cps. Triangular 1.32° Elevator Deflection Input, System 2	52
23.	Time History, .06 cps. Triangular 1.32° Elevator Deflection Input, System 1-a	53
24.	Time History, .06 cps. Triangular 1.32° Elevator Deflection Input, System 1-b	54
25.	Time History, .06 cps. Triangular 1.32° Elevator Deflection Input, System 2	55
26.	Time History, .06 cps. Triangular 1.32° Elevator Deflection Input, Basic Airframe	56
27.	Time History, Human Pilot Controlled Flight on Glide Slope, System 1-a	57
28.	Time History, Human Pilot Controlled Flight on Glide Slope, System 1-b	58
29.	Time History, Human Pilot Controlled Flight on Glide Slope, System 2	59
30.	Time History, Human Pilot Controlled Flight on Glide Slope, Sinusoidal Input of 5 Knots Horizontal Gust, System 1-a	60

31. Time History, Human Pilot Controlled Flight on Glide Slope, Sinusoidal Input of 5 Knots Horizontal Gust, System 1-b	61
32. Time History, Human Pilot Controlled Flight on Glide Slope, Sinusoidal Input of 5 Knots Horizontal Gust, System 2	62
33. Time History, Human Pilot Controlled Flight on Glide Slope, Sinusoidal Input of 5 Knots Horizontal Gust, without Auto-Throttle	63
34. Time History, 5 Knots Step Horizontal Gust Input, Anti-Thrust System	64
35. Time History, 5 Knots Step Horizontal Gust Input, Anti-Thrust System with Changed Gain Constants	65
Appendix I, Table I-A	
Longitudinal Dimensional Stability Derivative Parameters	69
Appendix I, Table I-B	
Longitudinal Non-Dimensional Stability Derivatives	70
Appendix I, Table II	
Dimensional Stability Derivatives	71
Appendix II, Table I	
Program Symbols and Meanings	75
Appendix II, Fig. 1	
Sample Data Cards, LONGSTAB	77
Appendix II, Fig. 2	
Fortran Program LONGSTAB	80
Appendix III, Table I	
Potentiometer Settings	90
Appendix III, Table II	
Scale Factors Used in Analog Simulation	92
Appendix III, Table III	
Potentiometer Setting Calculations	94
Appendix III, Fig. 1	
Analog Schematic, Airframe Equations of Motion	98

Appendix III , Fig. 2		
Analog Schematic , System 1 Auto-Throttle , Aircraft		
Engine , Stick System Dynamics		99
Appendix III , Fig. 3		
Analog Mechanization , System 2 Auto-Throttle		101

TABLE OF SYMBOLS

For those symbols not defined in the text.

C_D	=	Drag coefficient, Drag/qS
C_{D_0}	=	Drag coefficient in trimmed condition
C_L	=	Lift coefficient, Lift/qS
a	=	$dC_L/d\alpha$, Lift curve slope
dC_D/dC_L	=	Rate of change of drag with lift
T	=	Thrust, lbs.
S	=	Wing area, sq. ft.
q	=	Dynamic pressure, $1/2 \rho V^2$, lbs./sq.ft.
V, U_0	=	Forward velocity, reference steady state, ft./sec.
V_{SL}	=	Stall velocity, ft./sec.
u	=	Perturbation forward velocity, ft./sec.
w	=	Perturbation vertical velocity, ft./sec.
γ	=	Flight path angle, measured from the horizontal, radians
θ	=	Pitch angle, measured from horizontal to FRL, radians
$\Delta ()$	=	Error quantity, increment, perturbation
n_z	=	Normal load factor, g units
ΔT_{dc}	=	Thrust command increment, lbs.
C_{AS}	=	Equivalent propulsion system drag = $-\frac{1}{S} \frac{\partial T}{\partial q}$
\tilde{T}	=	Time constant, time in seconds to reach 63% steady state
K_α	=	Gain constant for α input
K_{n_z}	=	Gain constant for n_z input

K_θ	=	Gain constant for pitch error input
K_{V1}, K_u	=	Gain constant for airspeed error input
$K_{V2}, K_f u$	=	Gain constant for integral of airspeed error input
ω_n	=	Undamped natural frequency, radians/sec.
ζ	=	Damping ratio

AN INVESTIGATION OF THE EFFECT OF AUTO-THROTTLE DEVICES ON AIRCRAFT CONTROL IN THE CARRIER LANDING APPROACH

1. Introduction

The carrier landing approach speed of current swept wing aircraft is influenced by many factors. One of the most important of these factors is often referred to as speed instability. Speed instability can be explained with the help of Fig. 1. It will be noted that for Aircraft "A", a slight deviation in airspeed from the normal approach speed makes very little difference in thrust required. This curve is typical of the AF-1E type aircraft. On the other hand, a deviation towards slower speed for Aircraft "B" causes a large increase in thrust required. This increase, if uncorrected, causes a loss of altitude. Thus, in effect, the normal approach of Aircraft "B" is made on the "backside" of the thrust versus airspeed curve. This curve is typical of the F-8 aircraft. Essentially this steep backside of the curve is caused by a high value of C_{Dx} , drag increase due to angle of attack (or lift).

Still another factor contributing to airspeed instability is slow engine response. With a comparatively long time lag in engine response, any hesitation on the part of the pilot in correcting an incipient airspeed loss leads to wide variations in altitude or airspeed before effective thrust can be realized.

With an aircraft that displays speed instability tendencies, either a faster approach speed or an automatic compensating device is required to prevent undesired altitude loss due to airspeed deviations. Faster

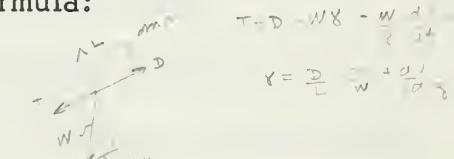
approach speeds are not desirable for carrier approaches. It will be the purpose of this paper to investigate some methods of applying automatic power compensation to counteract airspeed instability. A swept wing fighter, patterned after the F-8 airplane is used as the vehicle of the investigation. Both digital and analog computers are exploited in simulating auto-throttle and anti-drag system response to various inputs. Real-time, pilot controlled, analog simulated mirror approaches are also used in qualitatively evaluating each system.

This investigation is the first of a continuing series to be conducted at the U. S. Naval Postgraduate School to evaluate systems of automatic airplane control.

2. Discussion

The aircraft-carrier mirror-landing approach is made at a constant speed and a constant angle of glide slope. This type of approach allows precision control of the landing, a factor of the utmost importance in carrier operations. However, the approach is usually made at a minimum airspeed that is dictated by performance and/or aircraft flying qualities. Thus, the airspeed must be monitored closely while making flight path angle adjustments. A simplified equation (given in Ref. 1) shows that flight path angle, γ , is approximated by the formula:

$$\text{Eq. (1)} \quad \gamma \approx \frac{D}{L} - \frac{T}{W} + \frac{dV}{dt} \frac{1}{g}$$



$$T = D \quad W = \frac{C_L}{2} \rho V^2 S$$

$$\gamma = \frac{\partial}{\partial t} \left(\frac{C_L}{2} \rho V^2 S \right)$$

Flight path angle, then, is dependent on lift/drag (L/D) ratio, thrust/weight ratio, and rate of speed change. In the mirror approach the pilot can adjust γ and airspeed by manipulating the throttle and elevator. The manner in which each of these controls can be used, however, is dependent upon the L/D ratio. For aircraft with a high L/D ratio, the elevator is used to control γ , while thrust is used to maintain constant airspeed. With a L/D ratio in the vicinity of 4 - 5 the rate of speed change is large during maneuvers. If, in addition, the L/D ratio decreases with increasing C_L in the approach speed range then speed instability is accentuated.

A variation of lift/drag ratio versus lift coefficient for the F-8 airplane is shown as Fig. 2. It can be seen that at the approach speeds used, ($1.1 - 1.2 V_{SL}$), L/D decreases rapidly with increase in C_L . As reported in Ref. 1, pilots stated that in order to change γ for an

airplane of this class, increased reliance on thrust rather than elevator was necessary. In the case of the F-8 airplane, however, height response to throttle input is slow due to small thrust line angle of attack and negligible trim changes due to power. The F-8 pilot, therefore, is forced into using the stick as the primary flight path control. Then, since the airspeed mode of oscillation (the phugoid) is lightly damped, the aircraft will hunt about a new equilibrium airspeed and glide slope angle in response to an elevator deflection. These speed changes in the 5 to 10 seconds following elevator input are disturbing to the pilot.

Another way of interpreting airspeed instability is referred to in Ref. 2. A curve similar to Fig. 1 can be drawn for thrust required versus dynamic pressure, q . A definition of a stable speed regime can then be postulated as that portion of the curve where

$$\text{Ineq. (2)} \quad \frac{d T_{\text{required}}}{d q} > 0$$

To express this inequality in terms of the lift and drag coefficients, we use the fundamental equilibrium equations for level flight:

$$\begin{aligned} C_D' S q &= \text{Drag} = T_{\text{req}} \\ C_L S q &= \text{Lift} = W \end{aligned}$$

therefore $T_{\text{req}} = W \frac{C_D'}{C_L}$

and $q = \frac{W}{S C_L}$

and $\frac{d T_{\text{req}}}{d q} = \frac{d(W \frac{C_D'}{C_L})}{d(\frac{W}{S C_L})} = \frac{W d(\frac{C_D'}{C_L})}{\frac{W}{S} d(\frac{1}{C_L})}$

since W and S are constant.

$$\text{Therefore } \frac{d T_{req}}{d g} = \frac{s d \left(\frac{C_D'}{C_L} \right)}{d \left(\frac{1}{C_L} \right)}$$

which result is substituted into Ineq. (2).

$$\frac{s d \left(\frac{C_D'}{C_L} \right)}{d \left(\frac{1}{C_L} \right)} > 0$$

Since S is greater than 0, this implies that

$$d \left(\frac{C_D'}{C_L} \right) / d \left(\frac{1}{C_L} \right) > 0$$

Taking the differentials of numerator and denominator:

$$\frac{\frac{(-1)}{C_L^2} C_D' d C_L + \frac{1}{C_L} d C_D}{-\frac{1}{C_L^2} d C_L} = \frac{C_L d C_D' - C_D' d C_L}{-d C_L} > 0$$

or

$$\text{Ineq. (3): } \frac{C_D'}{C_L} - \frac{d C_D'}{d C_L} > 0$$

Thus, satisfaction of Ineq. (3) implies speed stability.

The C_D' term used above is composed of $C_D + C_{AS}$, where C_{AS} is equivalent propulsion system drag. C_{AS} is defined as

$$C_{AS} \triangleq -\frac{1}{S} \frac{\partial T}{\partial g}$$

or for constant altitude and slow speeds,

$$C_{AS} = -\frac{K}{S} \frac{\partial T}{\partial V^2}$$

C_{AS} is seen to be proportional to the negative of the thrust change with respect to the velocity change. Inequality (3) may then be written as

$$\text{Ineq. (4)} \quad I = \frac{C_D + C_{AS}}{C_L} - \frac{d C_D}{d C_L} > 0$$

A more sophisticated approach, based on the suppression of altitude disturbances by the pilot's use of the elevator, and originating with the basic equations of motion, would produce essentially the same inequality, with a small modification factor included. (See Ref. 2) The resulting inequality is

$$\frac{C_D + C_{AS}}{C_L} - \frac{\frac{dC_D}{dC_L}}{1 + \frac{C_D}{a}} > 0$$

However, the correction term, $C_{D/a}$, is of relatively small magnitude and may be ignored. From this same analysis the time constant, τ , of the subsidence of an airspeed error is shown to be proportional to:

Eq. (5) $\tau = K C_L \left(\frac{C_D + C_{AS}}{C_L} - \frac{dC_D}{dC_L} \right)$

Typical values of the parameter I for the F-8 are given below.

At $1.1 V_{SL}$, $I = .22 - .548 = - .328$, showing distinct speed instability.

At $1.2 V_{SL}$, $I = .200 - .222 = - .022$, a less unstable value.

From an examination of the speed instability parameter, Ineq. (4), it will be seen that positive stability can be produced if either drag in trimmed conditions (C_{DO}) or C_{AS} is artificially increased.

C_{DO} could be increased, for example, by extending the speed brakes during an approach. This would accomplish two objectives; one, increase C_{DO} in the stability formula, and two, cause the engine to operate in a higher RPM range to produce the added thrust necessary, thus effectively causing a slight decrease in the inherent engine time constant.

Remembering the definition for C_{AS} , the drag coefficient corresponding to the thrust/speed variation, it will be seen that an artificial means of increasing thrust with decreasing airspeed accomplishes the desired objective. This is exactly what automatic throttle or approach

power compensator devices are intended to do. Still another method of increasing C_{AS} is by the use of an anti-drag technique. This may be accomplished by having a drag producing device (such as side extending speed brakes) extended during the approach. Then, by using an airspeed controller type device to regulate the amount of drag produced (by opening or closing the speed brakes) in response to thrust (or anti-drag) required, airspeed deviations can be closely controlled. This particular method, within its limitations of having enough anti-drag available, theoretically has the advantage of a much shorter time lag than an engine response scheme.

3. Artificial Speed Stability through Automatic-Throttle Techniques

There is a choice of inputs to an automatic-throttle type controller, including various combinations of derivatives and integrals of airspeed error, pitch attitude error, angle of attack error, and normal acceleration. There are also many different philosophies by manufacturers concerning the ideal combination for best performance under all conditions. Two representative systems, one utilizing angle of attack and normal acceleration, and the other using airspeed error and pitch angle, were chosen for investigation.

A) Angle of Attack, Normal Acceleration Inputs

The Specialties, Inc. Automatic Power Compensator, (APC), an auto-throttle in use in the F-8 and F-4 aircraft, is an example of a control using these inputs. A block diagram, typical of this type of system is shown in Fig. 3. In this system, constant angle of attack is maintained in the landing approach using the two sensed inputs of instantaneous angle of attack and acceleration normal to the glide slope in g units. The normal g input supplies anticipation whenever the aircraft is not in a one g flight condition. A thrust command is calculated in the system computer dependent upon error signals and chosen gain and temperature factors. This thrust command then becomes an input to the engine which in turn adds an appropriate thrust to the airframe. This thrust, acting as the forcing function to the airframe modes of motion, changes the velocity of the aircraft. Thus the APC computer indirectly controls airframe velocity through the equations

$$\Delta T = K_x \Delta \alpha + K_n \Delta n_z ; \quad \Delta V = K_T \Delta T$$

Eq. (6) $\therefore \Delta V = K'_x \Delta \alpha + K'_n \Delta n_z$

where the K values are appropriate shaping, filtering and simulation networks.

Or, looking at it differently, the C_{AS} of Ineq. (4) has now been given a greater value $(C_{AS} \approx -\frac{\partial T}{\partial V})$

artificially, thus making the speed stability parameter more positive or stable.

The transfer function equations for this auto-throttle as supplied by Specialties, Inc., are also shown in Fig. 3. It will be noted that the throttle servo is simulated by a .1 second time constant first order lag. Angle of attack input is treated by both an integrator and lag network. Normal g input is also integrated.

The results of the analog simulation runs using this type of control are reported in Section IV of this paper, Experimental Methods and Results.

B) Pitch Angle, Airspeed Change Input

Flight path angle, γ , is given by the equation

Eq. (7) $\gamma = \theta - \alpha$

During constant airspeed flight, pitch attitude change ($\Delta \theta$) and flight path angle change ($\Delta \gamma$) are proportional; but dynamically, $\Delta \theta$ occurs before $\Delta \gamma$. Thus the means of anticipating flight path angle changes is available through pitch attitude changes recorded by a

vertical gyro mounted in the aircraft. This is the theory underlying the pitch angle, airspeed change type of automatic-throttle controller.

Through the use of a properly designed network, these inputs make it possible to minimize transient airspeed changes and to eliminate steady state airspeed changes resulting from variations in flight path.

The governing equation for this controller may be of the form:

$$\text{Eq. (8)} \quad \Delta T_{sc} = \left[K_\theta \Delta \theta - \frac{K_{V1} \Delta V}{(1 + \tau_a \Delta)} - \frac{K_{V2} \Delta V}{\Delta (1 + \tau_a \Delta)} \right]$$

Here the K_{V2} term is inserted as a steady state error washout term.

The lag term $(1 + \tau_a \Delta)$ simulates the airspeed sensor and filter. The filter attenuates the short period wind gust signals entering the system and acts as a smoothing influence.

This equation was reduced to a linear open loop transfer function of the auto-throttle controller. The block diagram for this system, combined with the analytically derived block diagram and transfer functions of the airframe and engine, are shown in Fig. 4. The stability derivatives for the F-8 in landing configuration were used for the airframe transfer functions. The derivation is shown in Appendix I.

The system open loop transfer function was calculated as:

$$\text{Eq. (9)} \quad -\frac{U}{U_e} = \frac{\left(\frac{\Delta T}{U_e}\right)_{AT} \left(\frac{U}{\Delta T}\right)_{AF}}{1 + \left(\frac{\theta}{\delta e}\right)_{AF} \left(\frac{\delta e}{U}\right)_{AF} \left(\frac{\Delta T}{\theta}\right)_{AT} \left(\frac{U}{\Delta T}\right)_{AF}}$$

where; $\left(\frac{\Delta T}{U_e}\right)_{AT} = \frac{1K_u + K_{se}}{s(1+1.16s)(1+s)}$

$$\left(\frac{U}{\Delta T}\right)_{AF} = \frac{-624 \times 10^{-5} (1 + 272s + 18.9s^2 + 23.25s^3)}{.416 (1 + 1.67s + 27.7s^2 + 2.08s^3 + 2.402s^4)}$$

$$\left(\frac{\theta}{se}\right)\left(\frac{se}{U}\right)_{AF} = \frac{-0.0142}{16.8} \frac{(1 + 37.9s + 176s^2)}{(1 + 5.29s + 0.01173s^2)}$$

$$\left(\frac{\Delta T}{\theta}\right)_{AT} = \frac{K_\theta}{(1+1.16s)}$$

This equation was programmed on the digital computer to produce a series of Nyquist plots, each utilizing different gain constants.

Fig. 5 shows the Nyquist plot for the equation using the same gain constants as were used in the analog simulation. From this figure the open loop gain margin is seen to be 19.2.

The system closed loop transfer function, $-\left(\frac{U}{U_{ref}}\right)$ was then derived.

This is shown symbolically as follows:

$$\text{Eq. (10)} \quad -\frac{U}{U_{ref}} = \frac{\left(\frac{\Delta T}{\Delta U}\right)_{AT} \left(\frac{U}{\Delta T}\right)_{AF}}{1 + \left(\frac{\Delta T}{\Delta \theta}\right)_{AT} \left(\frac{\theta}{se}\right) \left(\frac{se}{U}\right)_{AF} + \left(\frac{\Delta T}{U_e}\right)_{AT} \left(\frac{U}{\Delta T}\right)_{AF}}$$

A digital program was devised to calculate the values of the poles of the closed loop transfer function for various values of auto-throttle K's. This procedure would have produced families of Root Loci Plots. However, because of lack of time and computer malfunctions, this particular investigation was not completed. Equation (10) would be used in an optimizing analysis for gain constants.

In addition the equations of the auto-throttle were set up on the

the analog computer. This was incorporated into the complete system using approximately optimum values of K_{θ} , K_u , and $K_f u$. All simulation was done in real time. These results are also reported in Section IV. Analog mechanization is shown in Appendix III. A composite block diagram showing the relative positions of the two automatic throttle systems in the airspeed loop is presented as Fig. 6.

C) Auto-Throttle Controller Linked to Anti-Thrust Device

Another possible approach to the airspeed instability problem is the use of an auto-throttle controlling an anti-thrust or drag device. This could be accomplished by flying the approach with speed brakes extended. The output of the auto-throttle would then reduce or increase the drag by closing or opening the speed brakes as required. Thus, instead of supplying additional thrust when the airspeed drops, the speed brakes would be closed a proportionate amount, reducing the drag and in effect accomplishing the same purpose as an increase in thrust. Note that the time lag of the hydraulically actuated speed brake system is much less than that of the engine, thus allowing a faster response. The time constant of the hydraulic system is of the order of .1 second, while that of the F-8 engine is about 1.16 seconds. This approach was also investigated on the analog computer by replacing the engine with a first order time lag of .1 seconds (simulating the hydraulic system) and using the thrust command output of the auto-throttle computer to control the speed brakes.

Obviously the limiting feature to such a system is the amount of drag the speed brakes are capable of supplying. Of course it goes without saying that such a device can not be installed on an aircraft incapable of completing an approach while varying the positioning of the speed brakes. An airplane in this category is the F-8 which has a lower fuselage speed brake. Insufficient deck clearance is available when this brake is extended, thereby prohibiting its use during an approach.

4. Experimental Methods and Results

A) Equations and Analysis

The basic 3-degrees of freedom aircraft longitudinal equations of motion (in British notation) used in the analysis are shown below. The equations are based on the small perturbation linear theory. Lower case letters represent perturbation quantities. Upper case, subscripted o, letters represent initial steady state conditions. Body axes are used throughout. The assumptions made are as follows:

1. The airplane has a longitudinal plane of symmetry.
2. The direction of the relative wind, in steady flight, lies in the plane of symmetry, and in steady state, all angular velocities are zero.
3. Initial flight condition is wings level.
4. Products and squares of perturbation velocities are small and are ignored, and sines of all perturbation angles are approximated by the angle itself in radians.
5. The longitudinal modes of motion are independent of the lateral modes.
6. Structural deformations are not considered.

Three degree of freedom non-dimensional equations of motion, British notation: (See Ref. 3) Figure 7 displays angular definitions and signs.

X Force Equation:

$$\left[\frac{d}{dT} - x_u \right] \frac{u}{V_0} - x_w \frac{w}{V_0} - \left[x_o - \frac{x_g}{u_i} \frac{d}{dT} \right] \theta = X_T \Delta T$$

Z Force Equation:

$$-3u \frac{u}{U_0} + \left[\frac{d}{dT} - 3w \right] \frac{w}{U_0} - \left[(1 + \frac{\gamma \theta}{\mu}) \frac{d}{dT} \right] \theta = [3\gamma + 3i] \gamma$$

Moment Equation:

$$\left[-\frac{\mu_m u}{i_b} \right] \frac{u}{U_0} + \left[-\frac{m_{ur}}{i_b} \frac{d}{dT} - \frac{\mu_m w}{i_b} \right] \frac{w}{U_0} + \left[\left(\frac{d}{dT} - \frac{m_g}{i_b} \right) \frac{d}{dT} \right] \theta = \left[\frac{\mu_m \gamma}{i_b} \right] \gamma + \left[\frac{\mu_m \tau}{i_b} \right] \Delta T$$

where symbols are defined as follows:

$$\hat{t} = \frac{m}{\rho U S}, \text{ air secs.}$$

$$\frac{d(\)}{dT} = \frac{\hat{t} d(\)}{dt}$$

$$\gamma = \frac{t}{\hat{t}} \quad \begin{matrix} \text{real time} \\ \text{air secs} \end{matrix}$$

u = perturbation horizontal velocity, ft./sec.

w = perturbation vertical velocity, ft./sec.

γ = elevator deflection, positive down, radians

ΔT = change in thrust required, lbs.

$\frac{w}{U_0}$ = α , angle of attack, radians

θ = pitch angle, radians

i_b = $\frac{I_{by}}{m l_t^2}$, Inertia Coefficient

I_{yy} = Moment of inertia, slug - ft²

m = mass, slugs

l_t = tail length, ft.

μ = $\frac{m}{\rho S l_t}$ = relative density

C = mean wing chord, ft.

S = reference Wing area, square ft.

X = Force parallel to x - axis, lbs.

Z = Force parallel to z - axis, lbs.

M = Moment about lateral axis, lbs. - ft.

h	=	distance from thrust line to CG, ft.
x_u	=	$\frac{1}{2} \frac{\partial \left(\frac{X}{\frac{1}{2} \rho U^2 S} \right)}{\partial \left(\frac{u}{U} \right)}$ non-dimensional Force Stability derivative and similar identities obtained by permuting x, z and u, w independently.
x_g	=	$\frac{1}{2} \frac{\partial \left(\frac{X}{\frac{1}{2} \rho U^2 S} \right)}{\partial \left(\frac{g l_t}{U} \right)}$ non-dimensional stability derivative and similar identities obtained by permuting x, z
x_T	=	$\frac{1}{2} \frac{\partial \left(\frac{X}{\frac{1}{2} \rho U^2 S} \right)}{\partial T}$ non-dimensional stability derivative and similar identify obtained by permuting x and z, η and T
m_u	=	$\frac{1}{2} \frac{C}{l_t} \frac{\partial \left(\frac{M}{\frac{1}{2} \rho U^2 S c} \right)}{\partial \left(\frac{u}{U} \right)}$ non-dimensional moment stability derivative and similar identities obtained by permuting u and w
x_θ	=	$\frac{1}{2} \frac{\partial \left(\frac{X}{\frac{1}{2} \rho U^2 S} \right)}{\partial \theta}$ non-dimensional stability derivative and similar identities obtained by permuting x, z
\bar{m}_w	=	$\frac{1}{2} \frac{C}{l_t} \frac{\partial \left(\frac{M}{\frac{1}{2} \rho U^2 S c} \right)}{\partial \left(\frac{w}{U^2} \right)}$ non-dimensional stability derivative
m_T	=	$X_T \frac{h}{l_t}$ non-dimensional stability derivative; $h =$ distance from thrust line to C.G. position

The necessary stability derivatives were evaluated by making use of a longitudinal dynamic stability Fortran program, designated LONGSTAB. The program was compiled while undertaking the course in dynamic aircraft stability given at the Postgraduate School. This program computed the necessary British stability derivatives and then used these derivatives in the aerodynamic equations of motion. The resulting stability quartic was then solved, by the program, for the phugoid and short period complex roots. Finally, the periods and times to damp to 1/2 amplitude

were computed for both modes. Necessary aircraft parameters used by the program were taken from F-8 data supplied by Ling-Temco-Vought, Inc. or calculated. The program-computed stability-derivatives used in the investigation are shown in Table I, as are the other aircraft parameters. All program-computed derivatives, after necessary conversions were found to be in close agreement with those listed in Ref. 6¹. The computer program is explained in Appendix II. A sample printout is shown in Table II.

From the program printout, the phugoid period is 33.5 seconds and that of the short period mode is 6.06 seconds. Times to damp to 1/2 amplitude are 29.9 and 1.73 seconds respectively. Undamped natural frequency, ω_n phugoid, is calculated as .189 radians/sec., ζ as .123. Short period ω_n is calculated as 1.19 rad./sec., ζ as .360.

Ref. 6 lists a phugoid ω_n of 0.188 rad./sec., and a ζ of .12. Short period results found were listed as $\omega_n = 1.19$ rad./sec., $\zeta = 0.35$. The results given by LONGSTAB and those given by Ref. 6 are in excellent agreement.

Thus, as previously remarked, it is seen that the phugoid is very lightly damped.

¹Ref. 6 reports on the results of an investigation conducted along similar lines as the subject of this paper. The two investigations were performed concurrently and independently of each other. After completion, the results of the author's analysis were verified insofar as possible with those given in Ref. 6.

These non-dimensional equations of motion were dimensionalized for the analog simulation. The engine time lag and auto-throttle blocks were next added. Real time stick and throttle simulators were then introduced into the system, together with the F-8 linearized longitudinal control system dynamics supplied by Ling-Temco-Vought. All analog runs were conducted in real time. The analog computers used were Donner 3100 and 3400 machines. An eight channel Brush recorder was used to record the time histories.

The following types of computer runs were then conducted:

- (a) Transient analysis runs using step inputs of elevator deflection, horizontal velocity gusts, and pitch attitude; first with basic airframe alone and then with the two basic types of auto-throttle controllers incorporated. Finally sample runs were made with the speed brake device replacing the engine.
- (b) Optimizing runs using triangular inputs of elevator deflection, to determine the optimum gain for this type of forcing function.
- (c) Sinusoidal gust inputs.
- (d) Real time pilot controlled runs using a simulated glide slope, with and without the aid of the auto-throttle. Horizontal turbulence was also added to determine the controller effectiveness.

Analog mechanization diagrams are shown in Appendix III. Potentiometer settings are shown in Table 1 to Appendix III. Time histories for these runs are displayed in Figs. 10 to 35.

B) Evaluations of Experimental Analog Runs

The systems referred to are as follows:

System 1, Inputs of angle of attack, and normal acceleration in g units.

System Equation: $\Delta T = \frac{1}{1+1A} \left[\frac{K_\alpha \Delta \alpha}{1+.5A} - \frac{K_{\Delta V} \Delta V}{1+A} + \frac{K_\gamma \Delta \gamma}{A} \right]$

System 1-a gain constants;

$$K_\alpha = 1970 \text{ lbs./degree}$$

$$K_{\Delta V} = 280 \text{ lbs./knot}$$

$$K_\gamma = 183 \text{ lbs./degree - sec.}$$

System 1-b gain constants;

$$K_\alpha = 3420 \text{ lbs./degree}$$

$$K_{\Delta V} = 72 \text{ lbs./knot}$$

$$K_\gamma = 190 \text{ lbs./degree - sec.}$$

System 2, Inputs of pitch angle, airspeed error

System Equation: $\Delta T = K_\theta \Delta \theta - \frac{u}{1+.1A} \left[K_u + \frac{K_{fu}}{A} \right]$

Gain constants;

$$K_\theta = 318 \text{ lbs./degree}$$

$$K_u = 360 \text{ lbs./knot}$$

$$K_{fu} = 22.3 \text{ lbs./knot - sec.}$$

1) Step input of 1.32° up elevator deflection

Fig. 10 is the analog time history response to a 1.3° step of up elevator deflection, using the System 1-a auto-throttle. Airspeed displays a slight oscillatory tendency, reaching an equilibrium speed of $+.6\%$ of V_o (.8 kts. above V_o). Thrust is applied smoothly in response to demand.

Fig. 11 shows the response of System 1-b. This system had the gain factors optimized for a step input of horizontal gust velocity. Note the high airspeed overshoot due to step elevator input.

Fig. 12 is the same situation using System 2. Airspeed is much more highly damped as compared to Fig. 11. Equilibrium airspeed is -1% of V_o (1.39 kts. below V_o). Thrust is also applied smoothly.

2) 5 knots of horizontal gust input

Fig. 13 displays the record of System 1-a in response to this input. The system is oscillatory with an approximate damping ratio of $\zeta = .15$, $\omega_n = .677$ rad/sec. The initial velocity overshoot is 61% of initial error. These values of gain constants are less than optimum for this type of input disturbance.

Fig. 14 displays the response of System 1-b, which has been optimized to this input disturbance. Equivalent ζ is now .58, ω_n is .73 rad/sec. Thrust response is somewhat oscillatory. Final value of airspeed is +.2% of V_o .

Fig. 15 is the record of System 1. This shows a damped response with final airspeed of about -2.2% V_o . Thrust changes are less than that required by System 1.

3) 4° step input of pitch angle.

Fig. 16 shows the response of System 1-a to this input. Initial velocity transient is +.8% V_o or 1.12 kts. Steady state error is +.4% V_o . Thrust application is slightly oscillatory.

Fig. 17 shows System 1-b response. Initial velocity transient is .6% V_o . Steady state error is also .6% V_o .

Fig. 18 displays the response of System 1. Initial velocity transient amounts to +1.6% V_o . Airspeed damps to +.4% V_o steady state error in 13

seconds, reaching less than 1% error in 9 seconds.

Fig. 19 shows the response of the basic airframe to this same input disturbance, without the aid of the auto-throttle. Airspeed oscillation is $\pm 1\% V_o$, with a steady state value of about $.5\% V_o$.

4) Optimizing runs using triangular elevator input

Fig. 20 shows System 1-a under the influence of a .02 cps triangular elevator deflection (maximum amplitude 1.32°) forcing function. Airspeed error is kept within a range of $\pm 2\%$ to $\pm 1\%$ of V_o . Thrust varies within the range of +1600 to -2400 lbs. about the trim setting. Thrust application follows elevator movement closely.

Fig. 21 shows the reaction of System 1-b. Note how airspeed fluctuates $\pm 4\% V_o$ (± 5.56 kts.). Thrust has very noticeable oscillatory tendencies and gyrates within rather wide limits.

Fig. 22 shows System 2 under the influence of this same forcing function. Airspeed is seen to vary ± 1.7 kts. or $\pm 1.2\%$ of V_o . Thrust varies approximately 2400 lbs. about trim thrust. Application of thrust, however, is smoother and displays less hunting characteristics than shown by System 1-a.

Figs. 23, 24 and 25 show the response of these same systems to a triangular elevator forcing function of the same magnitude as previously, but of .06 cps frequency.

Fig. 26 shows the reaction of the airplane to this same forcing function without the benefit of the auto-throttle. Note airspeed deviation is less than that obtained with System 1-b engaged.

5) Human pilot controlled flight on simulated glide slope

For this series of runs a pilot flew the simulated airplane on the glide slope, using the auto-throttle. Glide slope reference was obtained from a zero centered panel meter. The zero voltage level was considered the correct glide slope. This is shown on Channel 1 of Figs. 27, 28 and 29. The pilot was then told to manipulate the stick to fly the aircraft to a new 4° higher glide slope. This corresponded to a + 14 volt reading on channel 1, or 14 volts on his reference meter. This simulated a low "meatball" on a mirror approach and the flight path correction necessary. This new flight path angle was held momentarily. The pilot was then told to fly the airplane down to a -4° glide slope, after which he was to return to the normal flight path (0 volts).

The response of the aircraft, and speed control is shown in Figs. 27, 28 and 29 for Systems 1-a, 1-b and 2 respectively.

It will be noted that Systems 1-a and 2 maintain airspeed close to within 1% of V_O , whereas System 1-b has much greater airspeed fluctuations. Thrust application is again much more oscillatory in System 1-b.

6) Human pilot controlled flight on glide slope with sinusoidal input of 5 knots horizontal velocity gust

Figs. 30 and 31 are records of System 1 runs utilizing a pilot controlled stick with a forcing function sinusoidal input of 5 knots of horizontal velocity, frequency .05 cps. The pilot was again attempting to fly the glide slope 4° up and down.

Fig. 32 is the record of the response to this same forcing function under the influence of the pilot and the System 2 auto-throttle.

Fig. 33 displays the record of the pilot attempting to maintain original glide slope while the aircraft was being influenced by a sinusoidal u turbulence forcing function, without the benefit of the auto-throttle.

7) Speed brake anti-thrust system

Fig. 34 shows the history of the speed brake anti-thrust system in response to a 5 knot horizontal velocity step input. Mechanically, the System 2 auto-throttle was used to supply a thrust command, but this thrust command was used to drive a .1 second time constant anti-drag device, simulating the movement of the speed brakes. It will be noted that in comparison with Fig. 15, (standard System 2 setup) response and damping is faster. It required 9 seconds for the transient to steady within 1% of V_{∞} in the case of Fig. 34, while it required 11 seconds for System 2.

Fig. 35 shows the response of the anti-thrust system to the same forcing function, but utilizing different gain factors. Response is more oscillatory.

C) Summary of Analog Results

From the foregoing evaluations it can be seen that the response of the different systems investigated is dependent upon the sensed variables and the applied forcing functions. System 1-a, optimized to an elevator deflection input, is marginal to unsatisfactory in performance when subjected to a horizontal gust input. On the other hand, system 1-b, using the same sensed variables, but with gains optimized to horizontal

velocity input, does not perform well when subjected to elevator deflection inputs. System 2, utilizing different sensed inputs, also displays varying reactions to each of the forcing functions.

In general, it can be seen that System 2 has the capability of a smoother application of thrust in response to an airspeed error. System 1 has the capability of a more highly damped response, but causes a more erratic application of thrust. Further investigation as to the optimum values of gain constants is required to accomplish the desired task more efficiently.

It is further recommended that additional sensed variables or integrals of such terms be added to the analog set-up to help optimize system response. A fruitful area might be to incorporate a normal g input to System 2 to help the damping characteristics. It is anticipated that further investigations along this line will be conducted at the U. S. Naval Postgraduate School. These investigations will attempt to utilize the simplified equations obtained by the elimination of the short period mode, to develop a more tractable analysis.

1 ~ r

2 ~ u

5. Conclusions

The two major approach power compensator systems investigated appear to have the capability of performing the desired task. The major difference are degree of anticipation and erraticism of thrust application. With proper choice of gains and input variables, it seems feasible that a composite system can be designed to provide the advantages of both individual systems.

The speed brake or anti-thrust system has the capability of providing faster response, but is limited by drag area available and the physical feasibility of approaching with speed brakes extended.

The preceding investigation has firmly convinced the author that an auto-throttle mechanism is an important contribution to carrier aviation safety. An aircraft that is difficult to fly in the approach because of inherent speed instability problems, can have its whole character changed by an auto-throttle. By removing the undesired instability an auto-throttle relieves the pilot of concentrating on airspeed control, thus allowing more precision in glide slope and line-up control. This advantage by itself, should tend to reduce the frequency of ramp accidents.

In addition, when an automatic landing system is considered, the pilot-controlled airspeed loop must be replaced by an automatic system to provide consistency and predictability of response.

Still another advantage of the automatic airspeed control system is the reduction of minimum approach speed below that recommended by the pilots when airspeed is controlled by manual throttle manipulation. In

addition the automatic device can be designed to provide the anticipation and instant response that can only be obtained from much actual pilot experience. Thus it is seen that the auto-throttle can act as the great equalizer in carrier approach training.

TABLE I

Computed F8 Stability Derivatives and Associated Aircraft Parameters
 British Non-Dimensional Notation

$$x_u = - .2630$$

$$x_w = .16996$$

$$x_q = 0.0$$

$$x_\theta = -.450$$

$$\dot{x}_u = -.90$$

$$\dot{x}_w = -1.5915$$

$$\dot{x}_q = -.5878$$

$$\dot{x}_\theta = -.0640$$

$$M_u = .006052$$

$$M_w = -.15896$$

$$\dot{M}_w = -.1422$$

$$M_q = -.5119$$

$$\mu_1 = 54.466$$

$$i_\beta = .7081$$

$$\hat{t} = 3.2772$$

$$C_L = .90$$

$$C_D = .263$$

$$C_T = .195$$

$$S_w = 375 \text{ ft}^2$$

$$C_{m_\alpha} = -.380$$

$$\Theta_0 = 8.1^\circ$$

$$\frac{\partial \epsilon}{\partial x} = .4772$$

C_g position = 24%

Weight = 22,000 lbs

V_0 = 139 kts = 234 ft/sec

Z_n = -.1949

M_n = -.349

X_T = $.2046 \times 10^{-4}$

M_T = $-.635 \times 10^{-6}$

INPUT PARAMETERS

TAIL AREA= .95.000 WING AREA= .375.0000 CL ALFA TAIL= 2.353000 LTA TAIL= 1.000000 BODY AREA= .477200
 BODY LENGTH= 52.80000 RHO= .0023780 GLE= 32.17000 WEIGHT= 22000.0000 LBS D EPSILCN/D ALFA= .477200
 INITIAL PITCH ANGLE= 8.10000 DEGREES THRUST LINE LISTANCE= -.43700 FEET THRUST CCEF CT= .195000
 CMALFA= -.38000C I SUP YY= .96000.000 SLUG FT SQUARED

STABILITY DERIVATIVES

FORWARD VELOCITY= 234.000 T CARAT= 3.277273 Q= 65.1049
 C SUBL= .900000 C SUBD= .263000
 XU= -.2630 XW= .16996 XQ= .0000 XTHETA= -.45000 ZU= -.90000 ZW= +1.5915 TOTAL ZQ= -.5878
 ZTHETA= -.0640 MU= .006052 MW= -.15896 MBAR W'DATA= .1422 MC= -.5119 MUCNE= 54.466 I SUB BETA= .7081
 A= 1.00000 B= 2.77604 C= 14.04677 D= 3.020290 E= 5.0845394

THE VALUE OF ROUTHS DESCIMINANT = 69.47
 THE AIRCRAFT IS STABLE

RUN 3 C.G. 24, V=139 KTS, 234 FPS 3/3/63 LEVEL FLITE
 THE COEFFICIENTS OF THE GIVEN POLYNOMIAL ARE

REAL PART	1.0000000	2.7760450	14.0467662	3.0202908	5.0845393
IMAGINARY PART	.0000000	.0000000	.0000000	.0000000	.0000000

TABLE OF ROOTS

ROOT NUMBER	REAL PART OF ROOT	IMAG PART OF RCCT	PERIOD	TIME TO CAMP TO HALF AMPL
1	-.075930	-.614444	.5128 SECS	29.9173 SECS
2	-.075930	.614444	.5128 SECS	29.9173 SECS
3	-1.312092	-3.397553	6.0667 SECS	1.7313 SECS
4	-1.312092	3.397553	6.0667 SECS	1.7313 SECS

Table II

Sample Printout, Fortran Stability Program,
 LONGSTAB

Fig. 1
Thrust Required Versus Airspeed

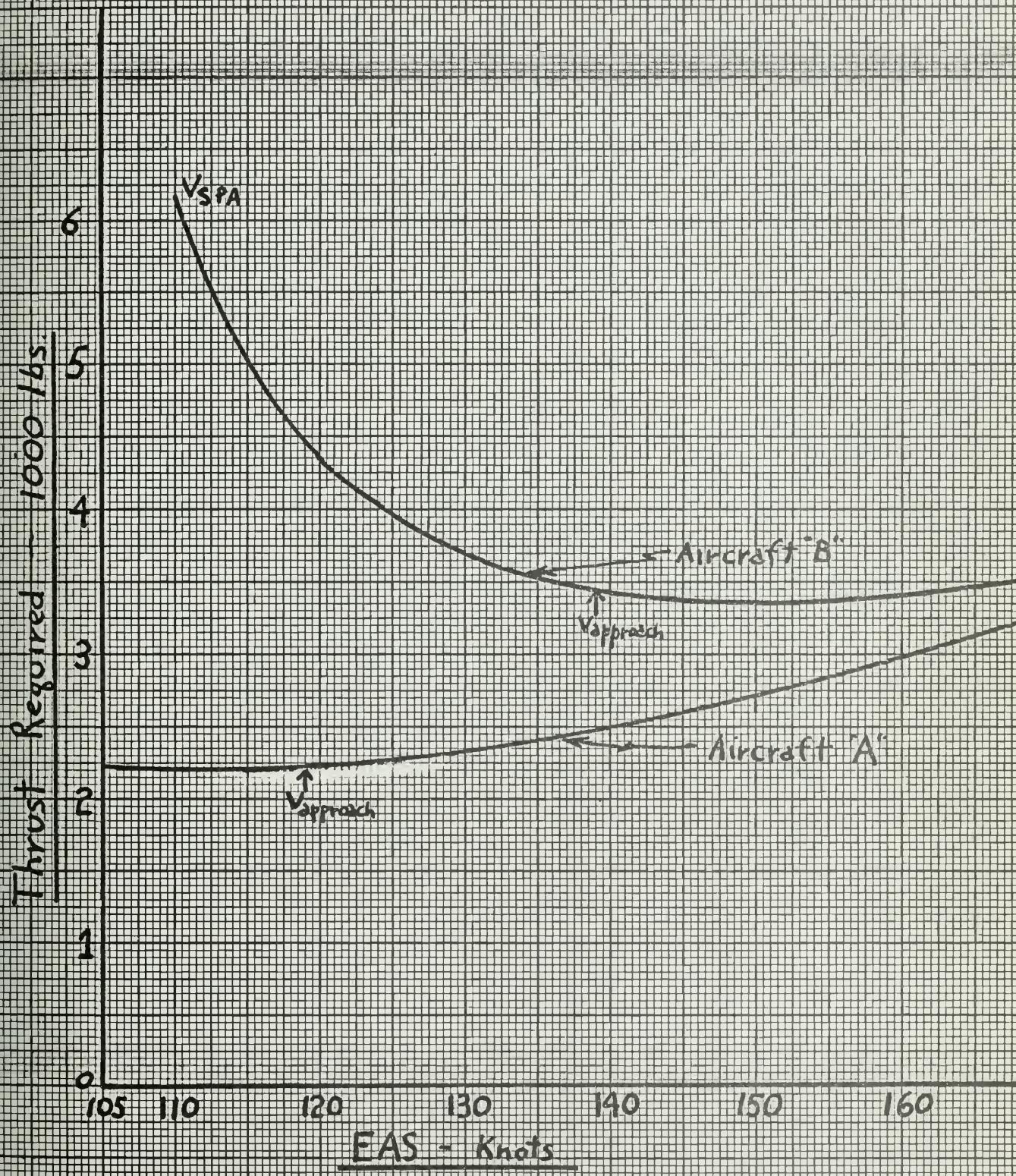


Fig. 2

C_L versus L/D , F-8 Airplane

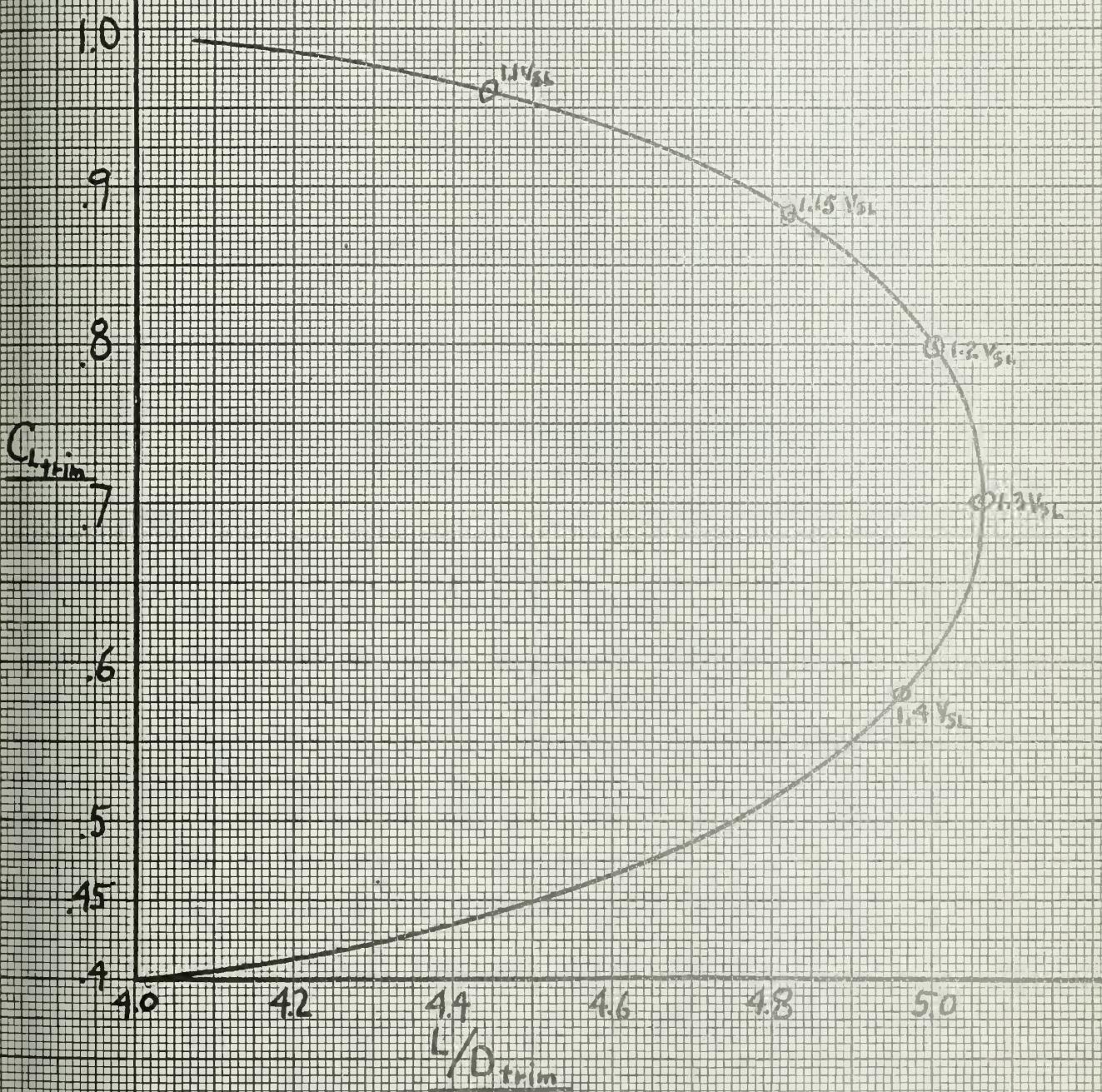
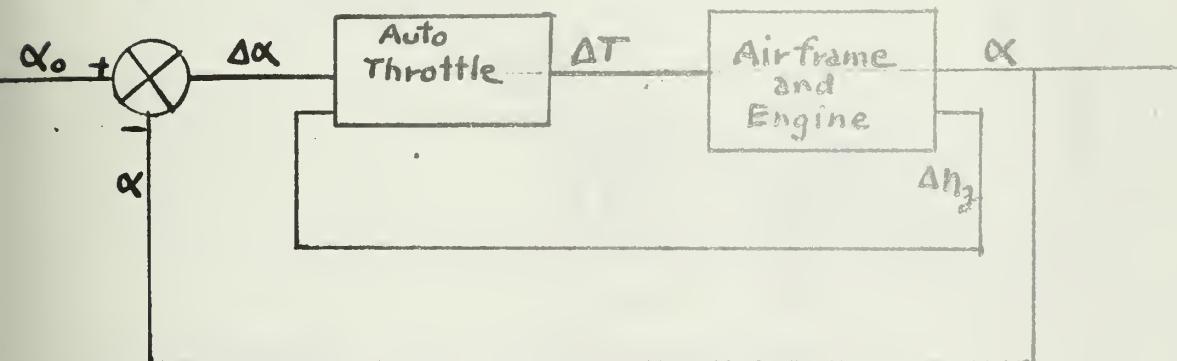


Fig. 3

Block Diagram, System 1 Auto-Throttle with Transfer Functions



Auto throttle Equation:

$$\Delta T = \frac{1}{1 + \zeta_1 A} \left[\frac{K_\alpha \Delta \alpha}{1 + \zeta_2 A} - \frac{K_V \Delta V}{1 + A} + \frac{K_\alpha \Delta \alpha}{A} \right]$$

Where:

ΔT = Thrust Command

$\Delta \alpha$ = Angle of attack error

α_0 = Reference Angle of attack

α = True Angle of attack

Δn_z = change of normal acceleration

$\Delta V = \frac{V_0}{2} (\Delta n_z - \frac{\Delta \alpha}{\alpha_0})$, speed change parameter

V_0 = Reference Airspeed

K_α = Angle of attack gain factor

K_V = Speed Change gain factor

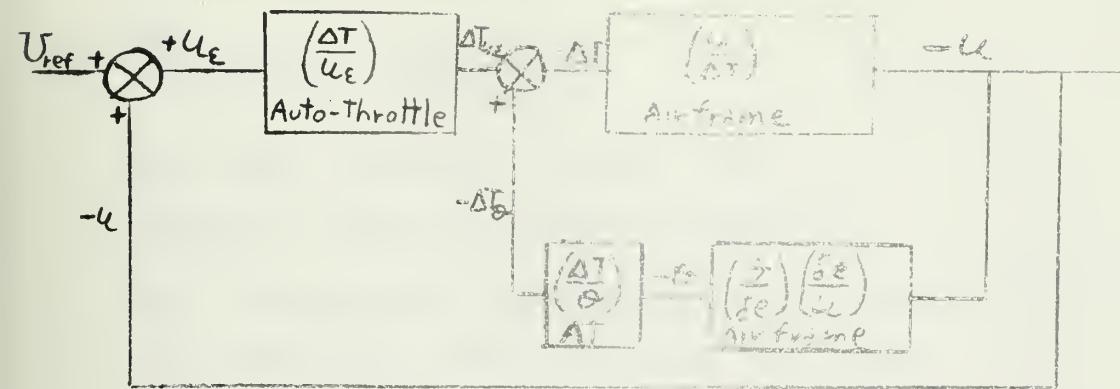
K_γ = Integral of angle of attack gain factor

ζ_1 = Servo and actuator time lag (.1 sec)

ζ_2 = Angle of attack shaping time lag. (.5 sec)

Fig 4

Block Diagram, System 2 Auto Throttle and Engine with Transfer Functions



Auto Throttle and Engine Equation:

$$\Delta T = \frac{1}{1+T_e s} K_\theta \theta - \frac{U_e}{(1+T_e s)(1+T_f s)} \left[U_{ref} + \frac{K_{Iu}}{s} \right]$$

T_e = Engine Time Constant

T_f = Airspeed Sensor Time Constant

θ = Pitch Angle Change

U_{ref} = Reference Airspeed

U_e = Airspeed Error

K_u = Airspeed Gain Constant

K_{Iu} = Integral of Airspeed Gain Constant

K_θ = Pitch Angle Gain Constant

$$\left(\frac{\Delta T}{U_e} \right)_{AT} = \text{Auto Throttle Transfer Function} = \frac{K_u + \frac{K_{Iu}}{s}}{(1+T_e s)(1+T_f s)}$$

$$\left(\frac{\Delta T}{\theta} \right)_{AT} = \text{Auto Throttle Transfer Function} = \frac{K_\theta}{(1+T_e s)}$$

$$\left(\frac{U}{\Delta T} \right)_{\text{Airframe}} = \text{Airframe Transfer Function} = \frac{K_{h_1} N_1(s)}{K_D + D_1(s)}$$

Fig. 4 (continued)

$$\left(\frac{\delta e}{e}\right)_{\text{Airframe}} = \frac{K_{D1} D_1(s)}{K_{N2} N_2(s)}$$

$$\left(\frac{\theta}{\delta e}\right)_{\text{Airframe}} = \frac{K_{N3} N_3(s)}{K_{D1} D_1(s)}$$

$$K_{N1} = \text{Gain Constant} = .624 \times 10^{-5}$$

$$N_1(s) = [1 + 272s + 18.9s^2 + 23.25s^3]$$

$$K_{D1} = \text{Characteristic Equation Gain Constant} = .416$$

$$D_1(s) = \text{Stability Characteristic Quartic}$$

$$= [1 + 1.67s + 27.7s^2 + 208s^3 + 2.462s^4]$$

$$K_{N2} = \text{Gain Constant} = 16.8$$

$$N_2(s) = [1 + 5.29s + 0.01173s^3]$$

$$K_{N3} = \text{Gain Constant} = -0.142$$

$$N_3(s) = [1 + 37.9s + 178s^3]$$

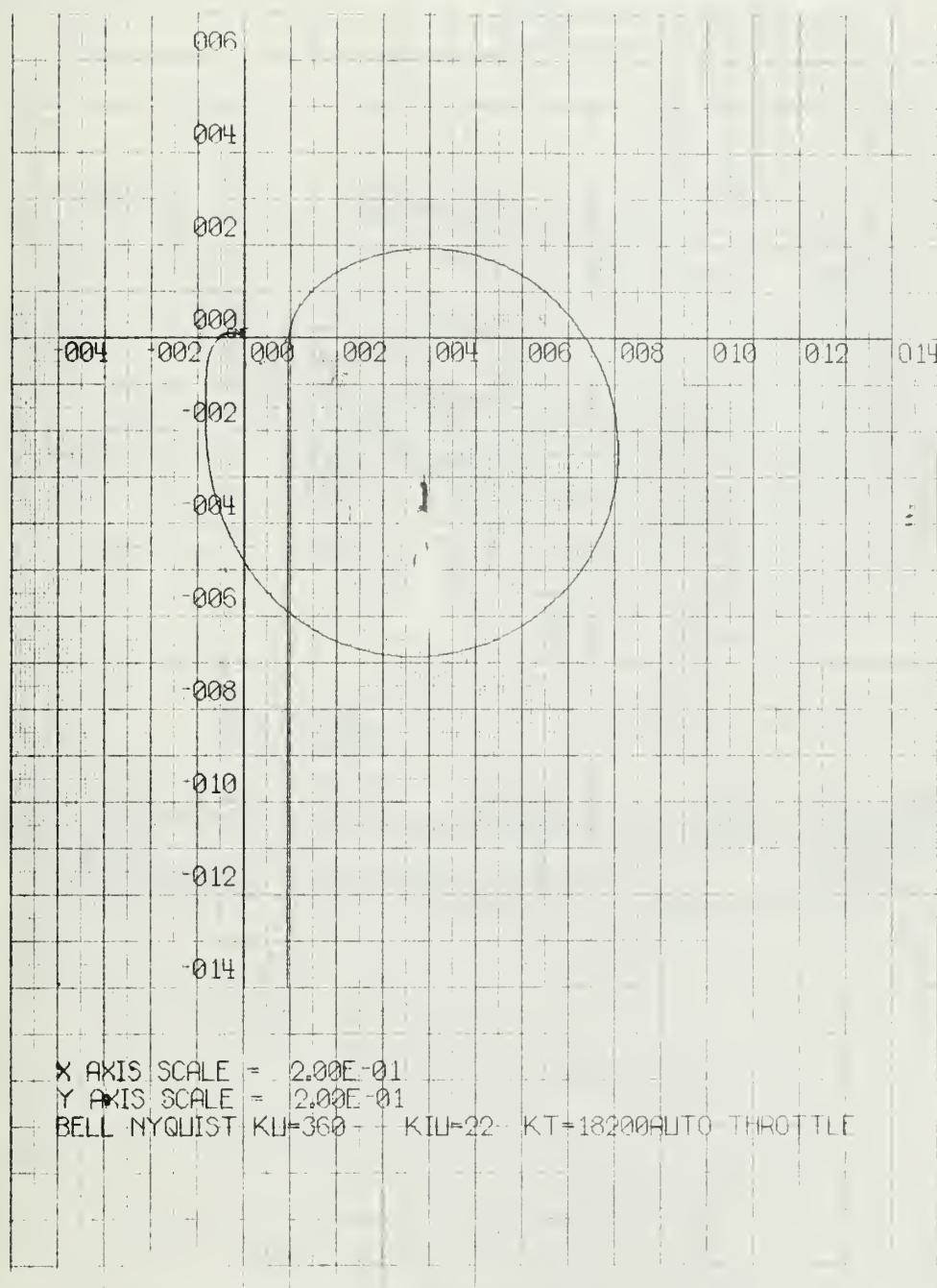


Fig. 5

Nyquist Diagram of System 2 Auto-Throttle
 Open Loop Transfer Function

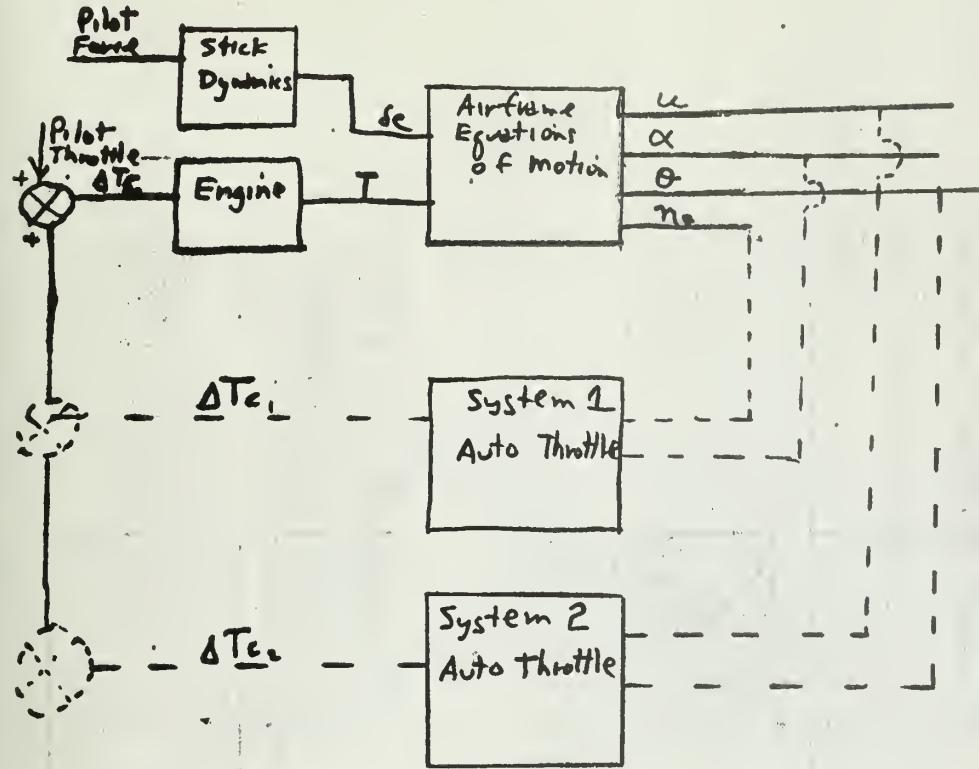


Fig. 6

Composite Block Diagram of Complete
Automatic Throttle-Airframe System

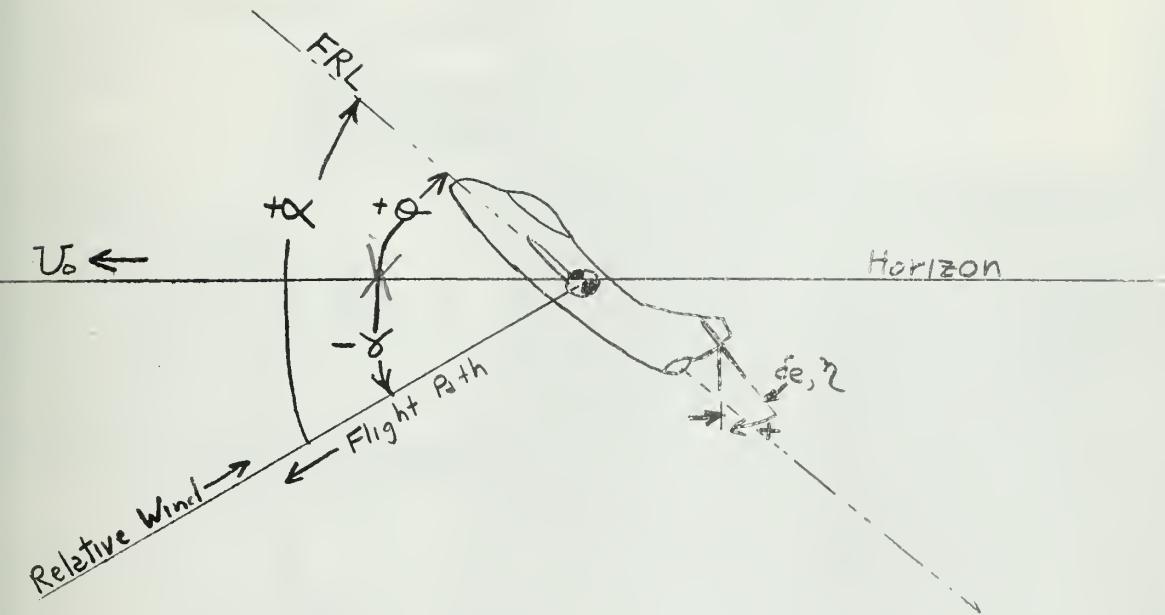


Fig. 7

Angular Definitions and Signs



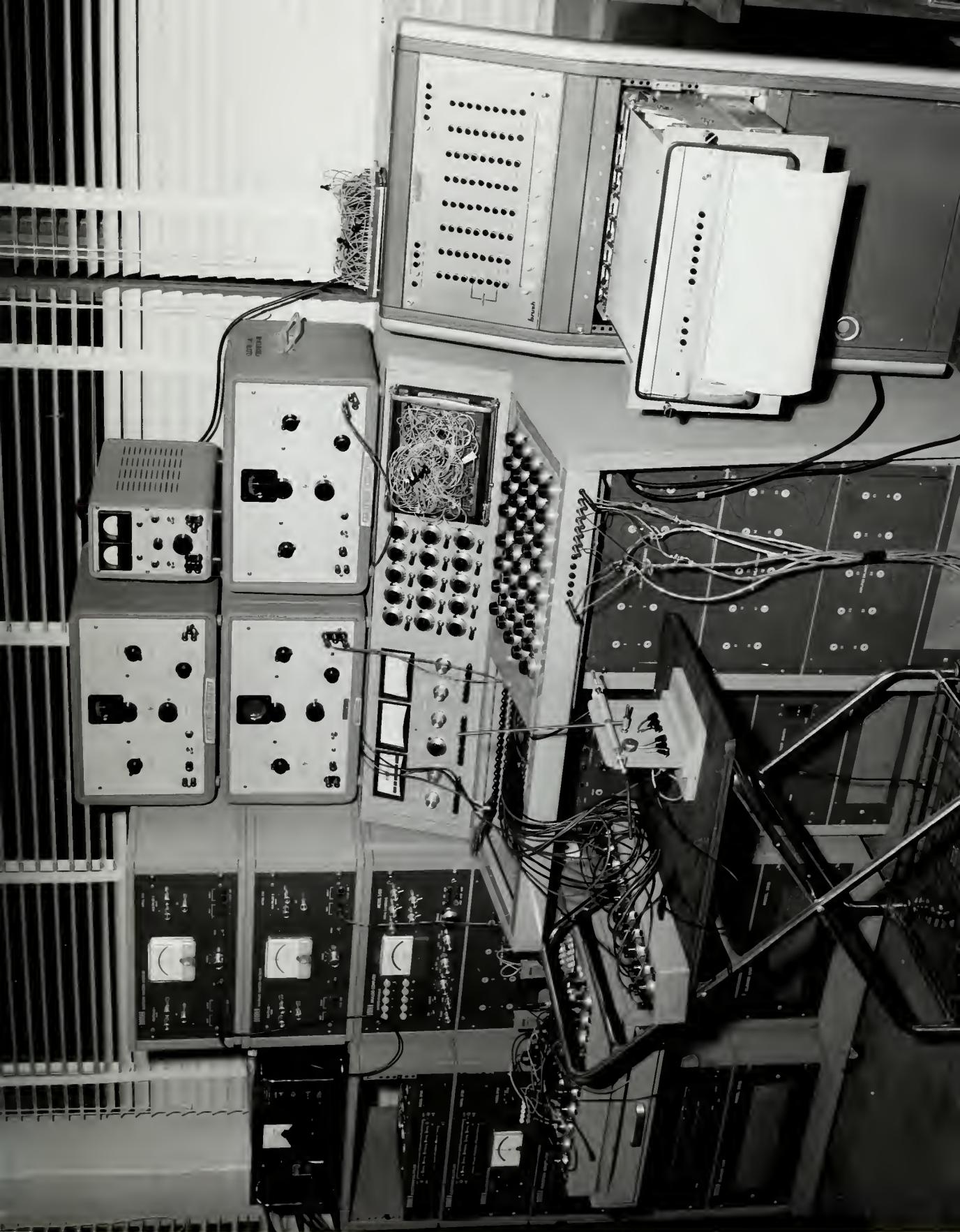


Fig. 8
Analog Computer Setup
38





Fig. 9
Analog Computer Setup
39

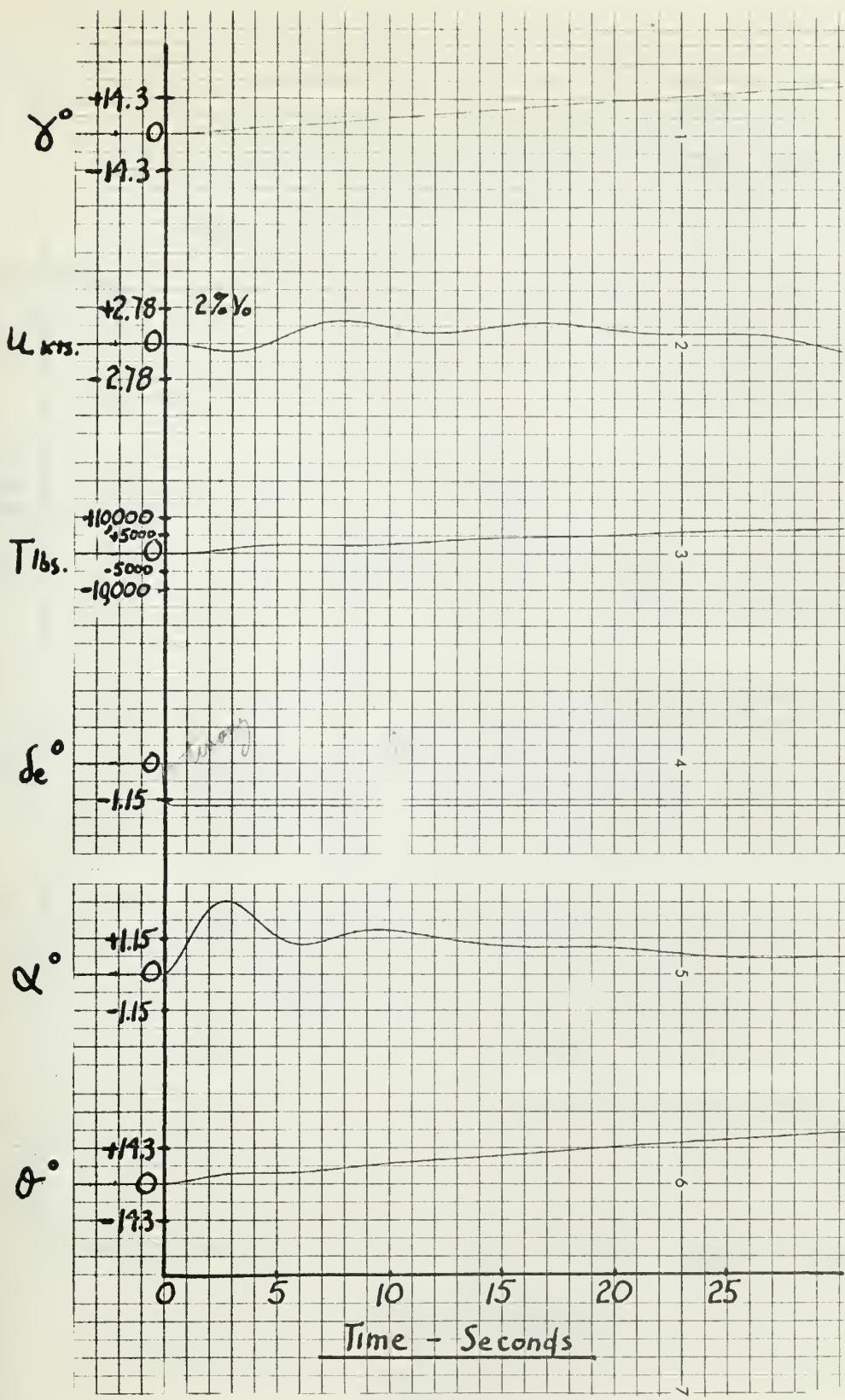


Fig. 10

Time History, 1.3° Up Elevator Deflection Input,
System 1-a

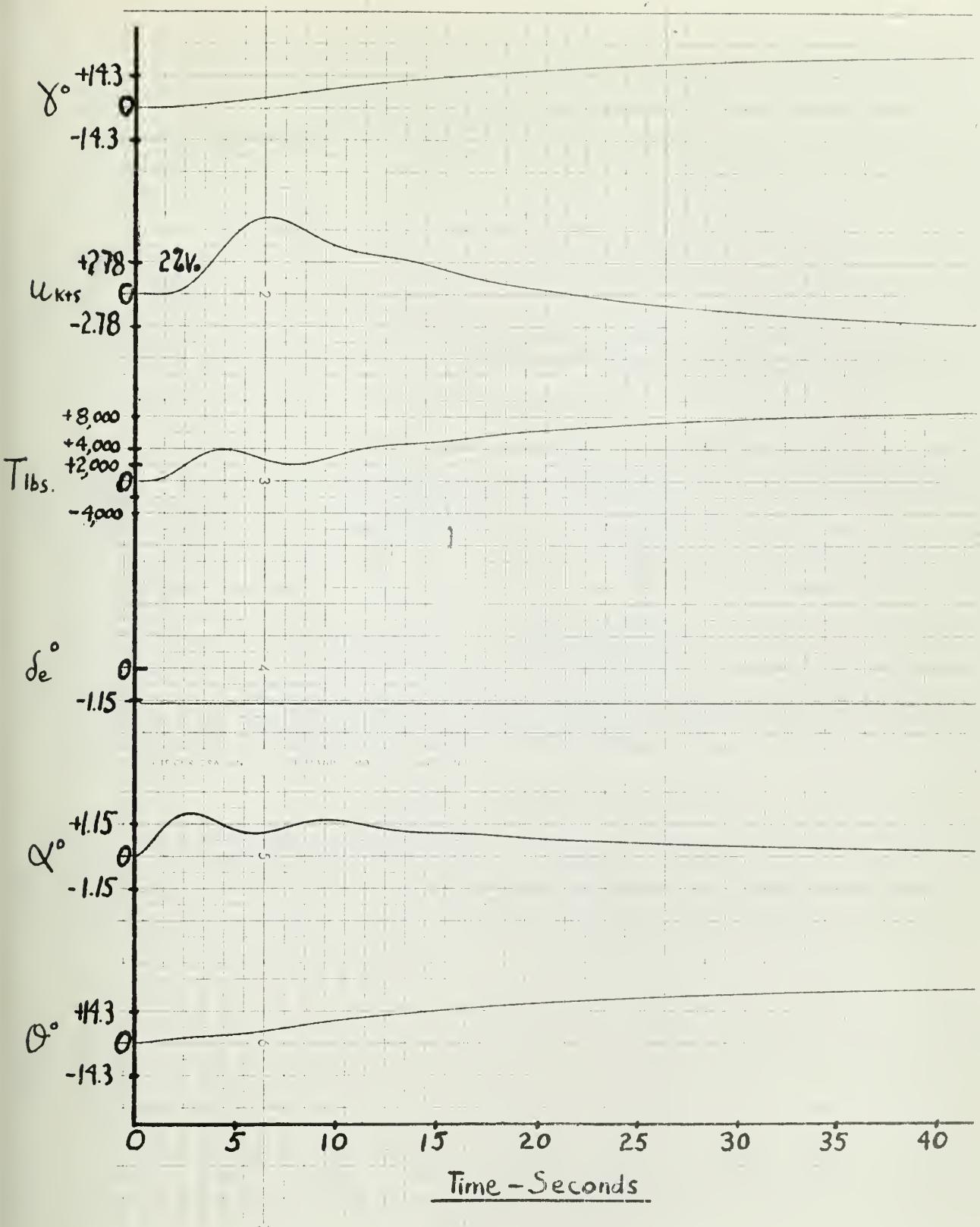


Fig. 11

Time History, 1.3° Up Elevator Deflection Input,
System 1-b

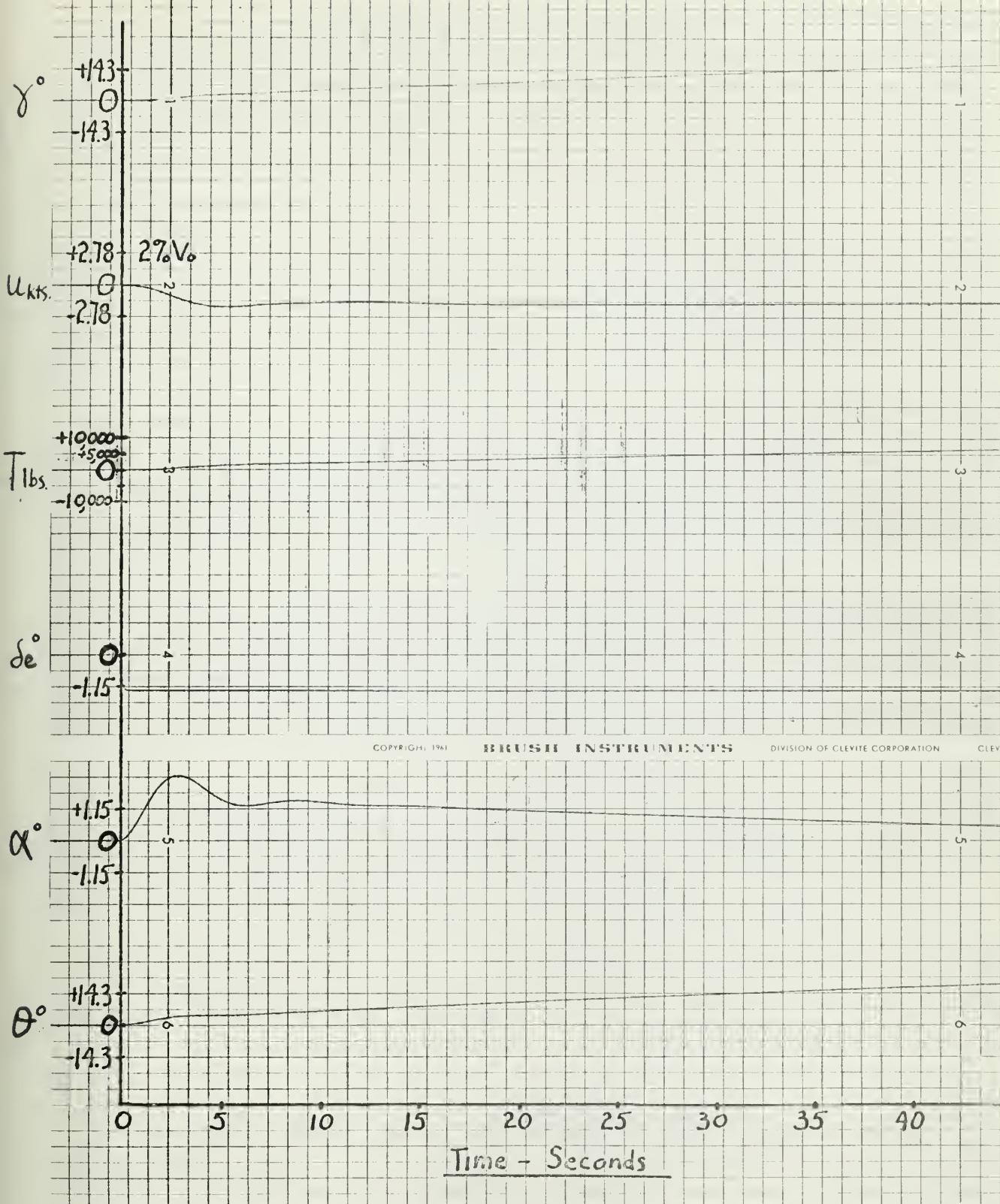


Fig. 12

Time History, 1.3° Up Elevator Deflection Input,
System 2 i.e. θ, α

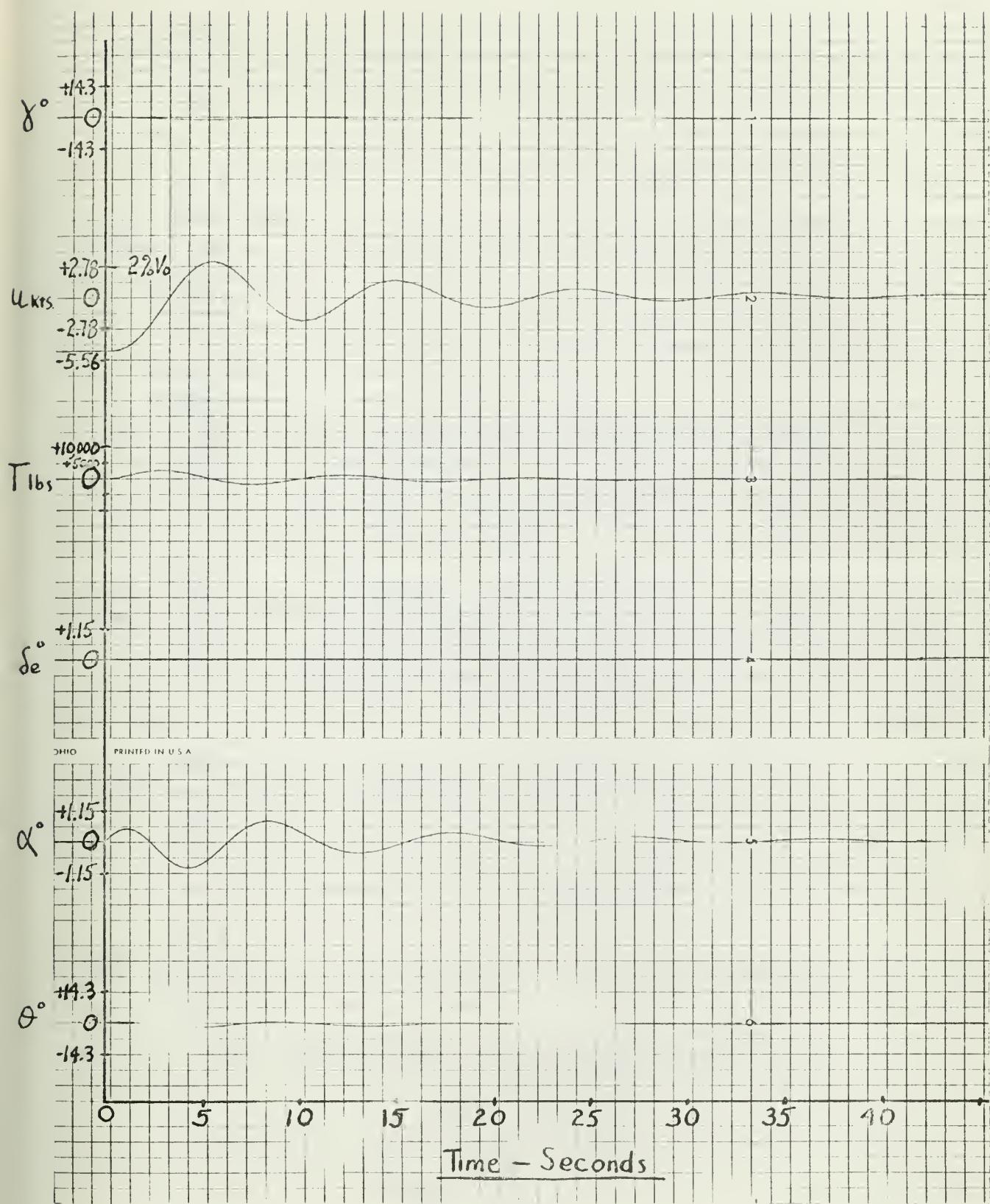


Fig. 13

Time History, 5 Knots Horizontal Gust Input,
System 1-a

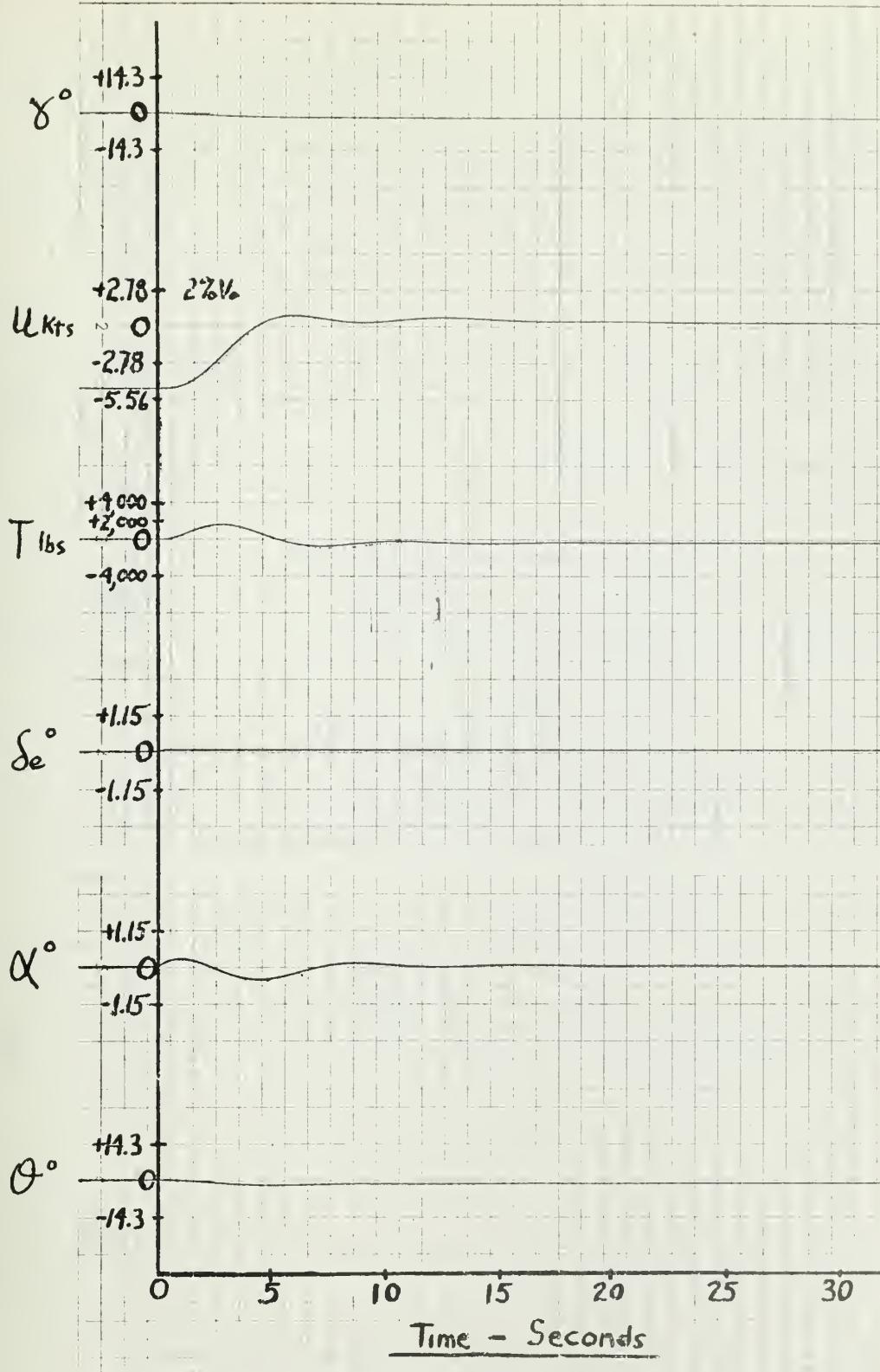


Fig. 14
Time History, 5 Knots Horizontal Gust Input,
System 1-b

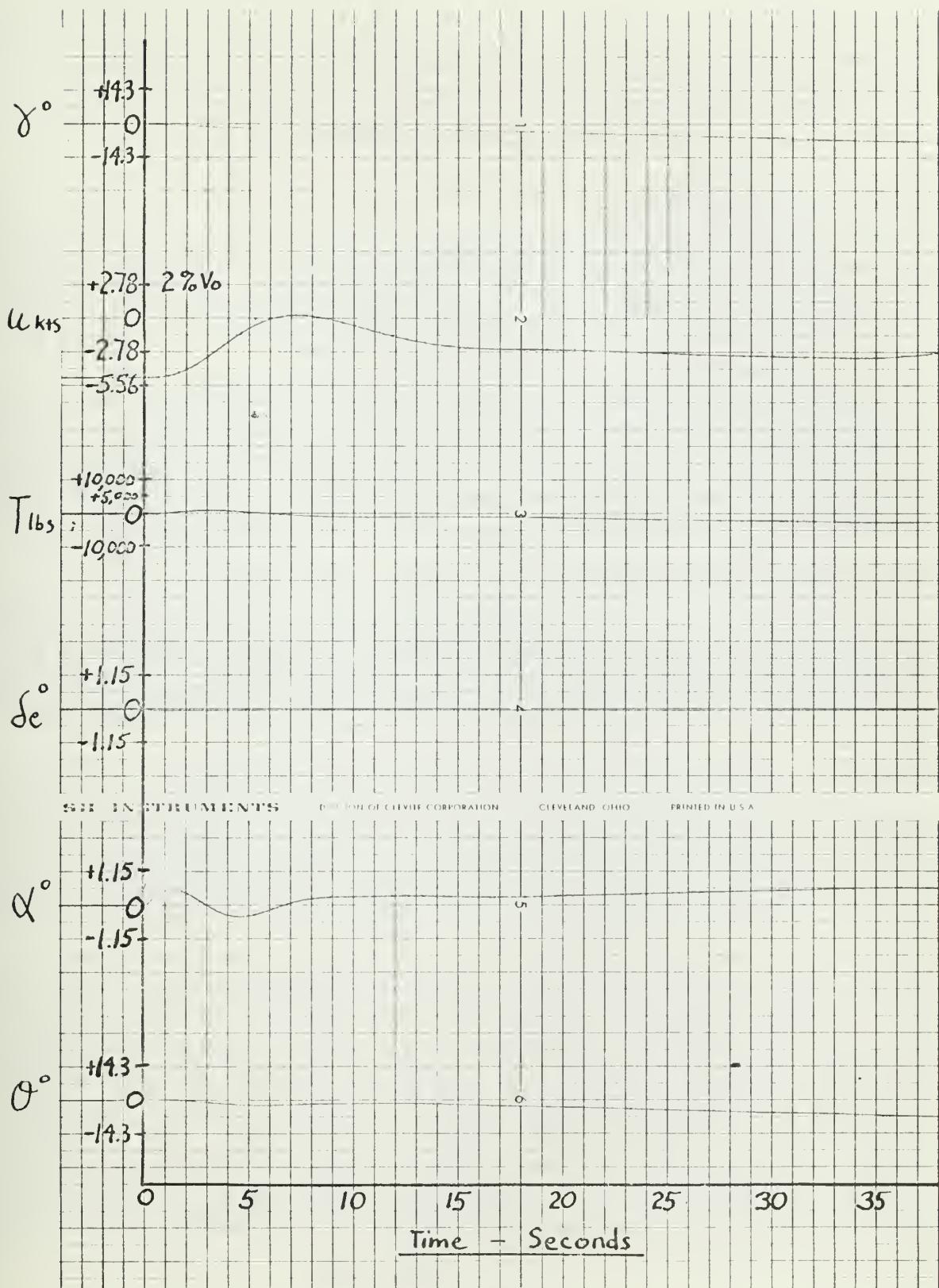


Fig. 15

Time History, 5 Knots Horizontal Gust Input,
System 2

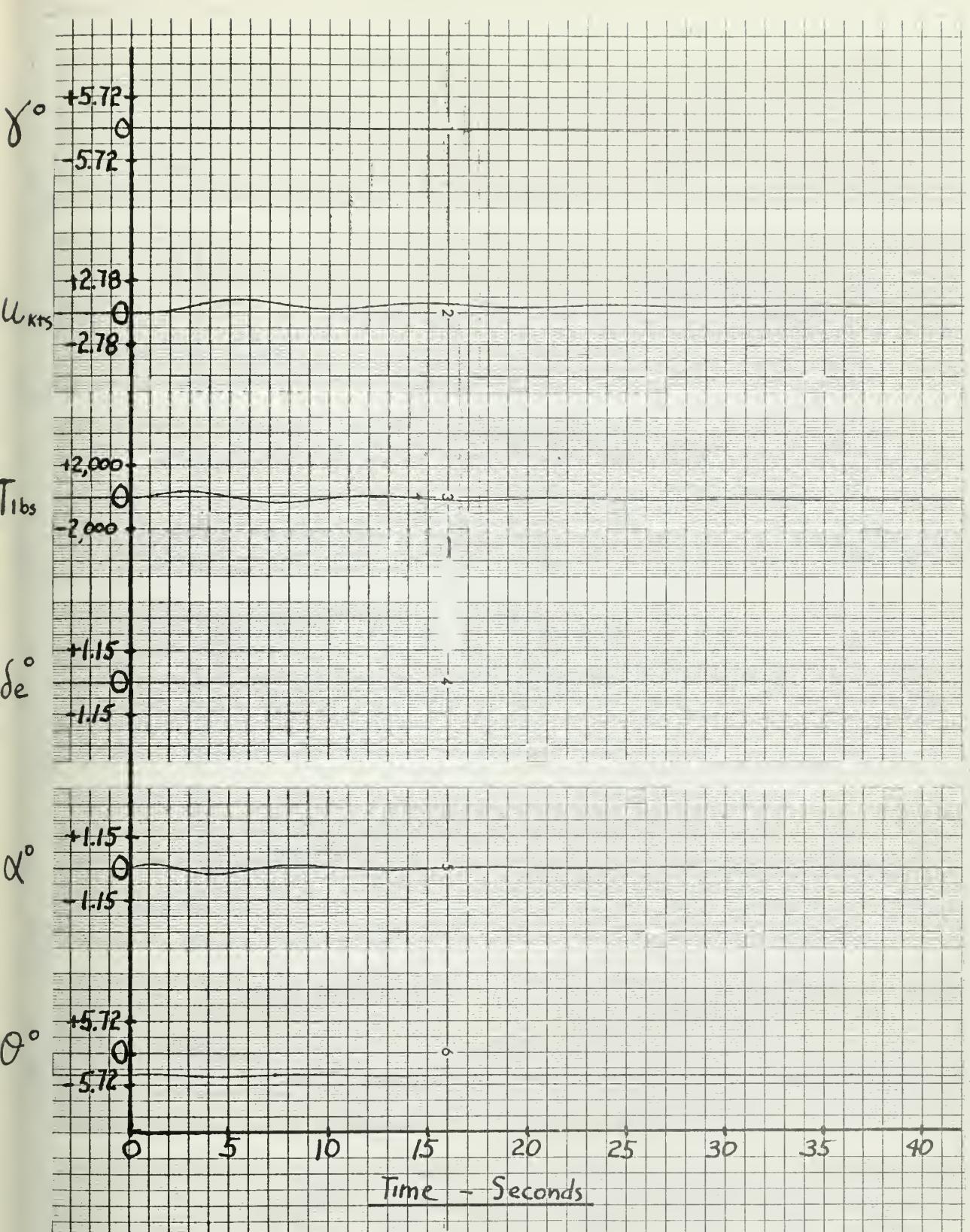


Fig. 16

Time History, 4° Step Input Pitch Angle, θ ,
System 1-a

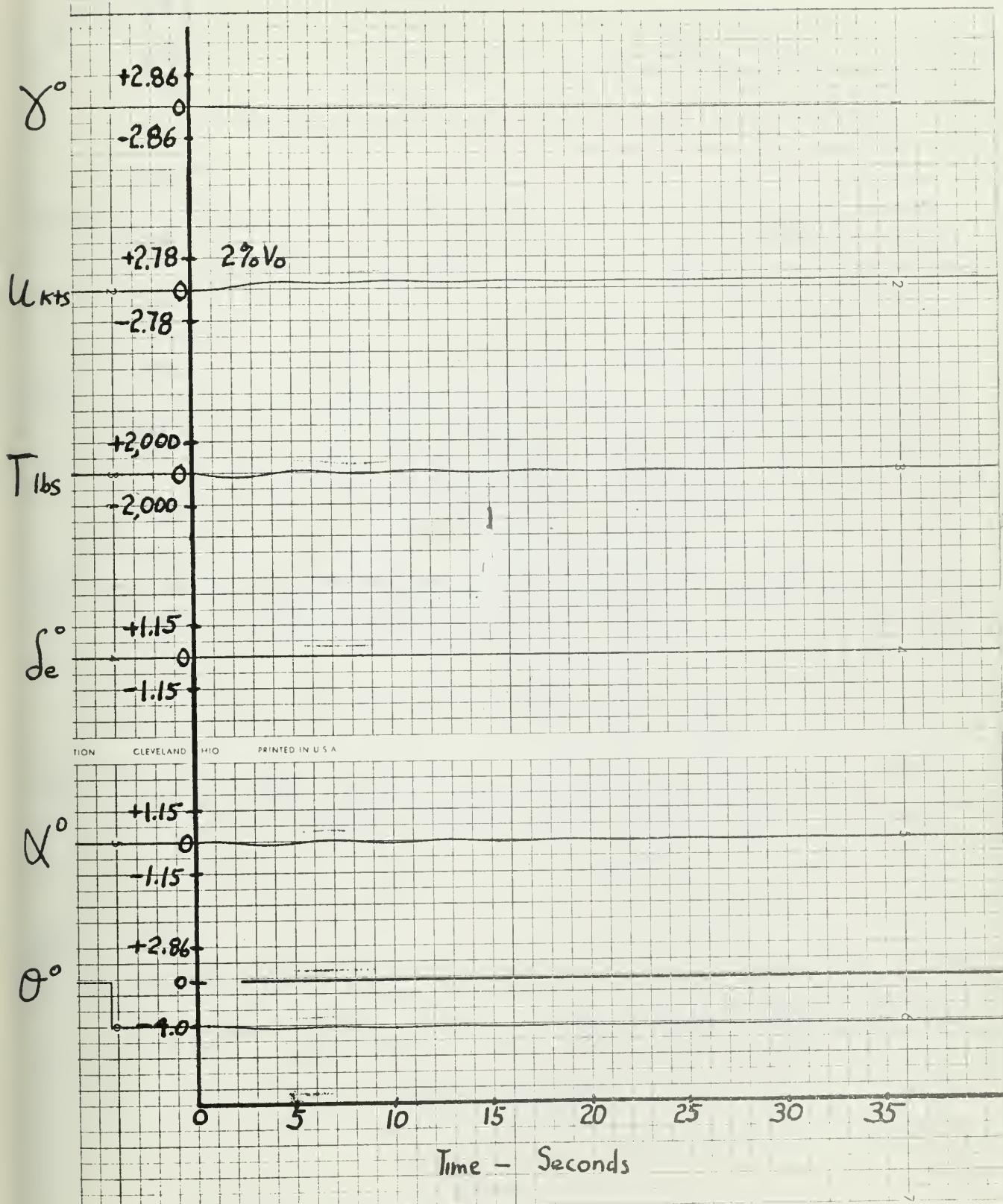


Fig. 17

Time History, 4° Step Input Pitch Angle, θ ,
System 1-b

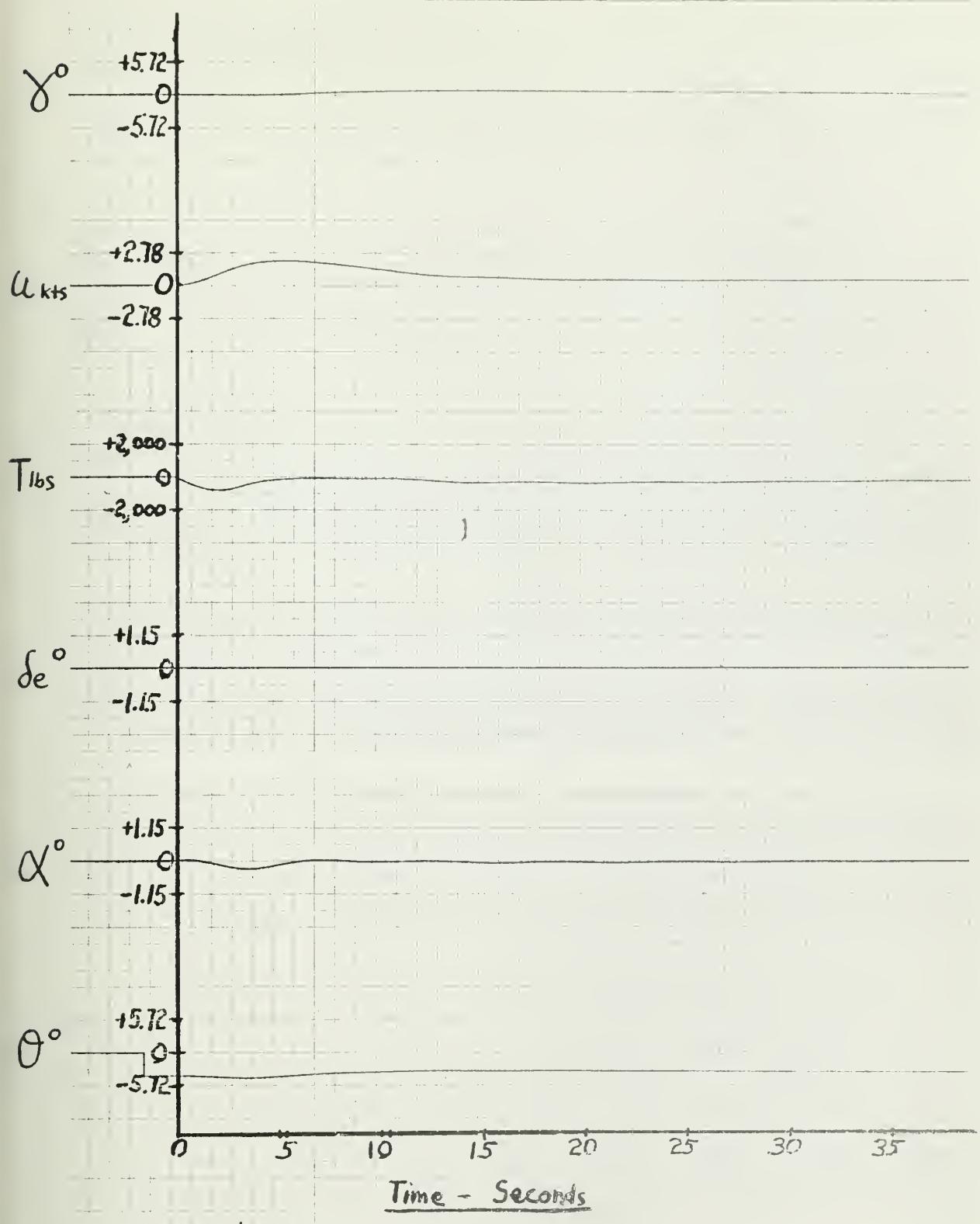


Fig. 18
Time History, 4° Step Input Pitch Angle, θ ,
System 2

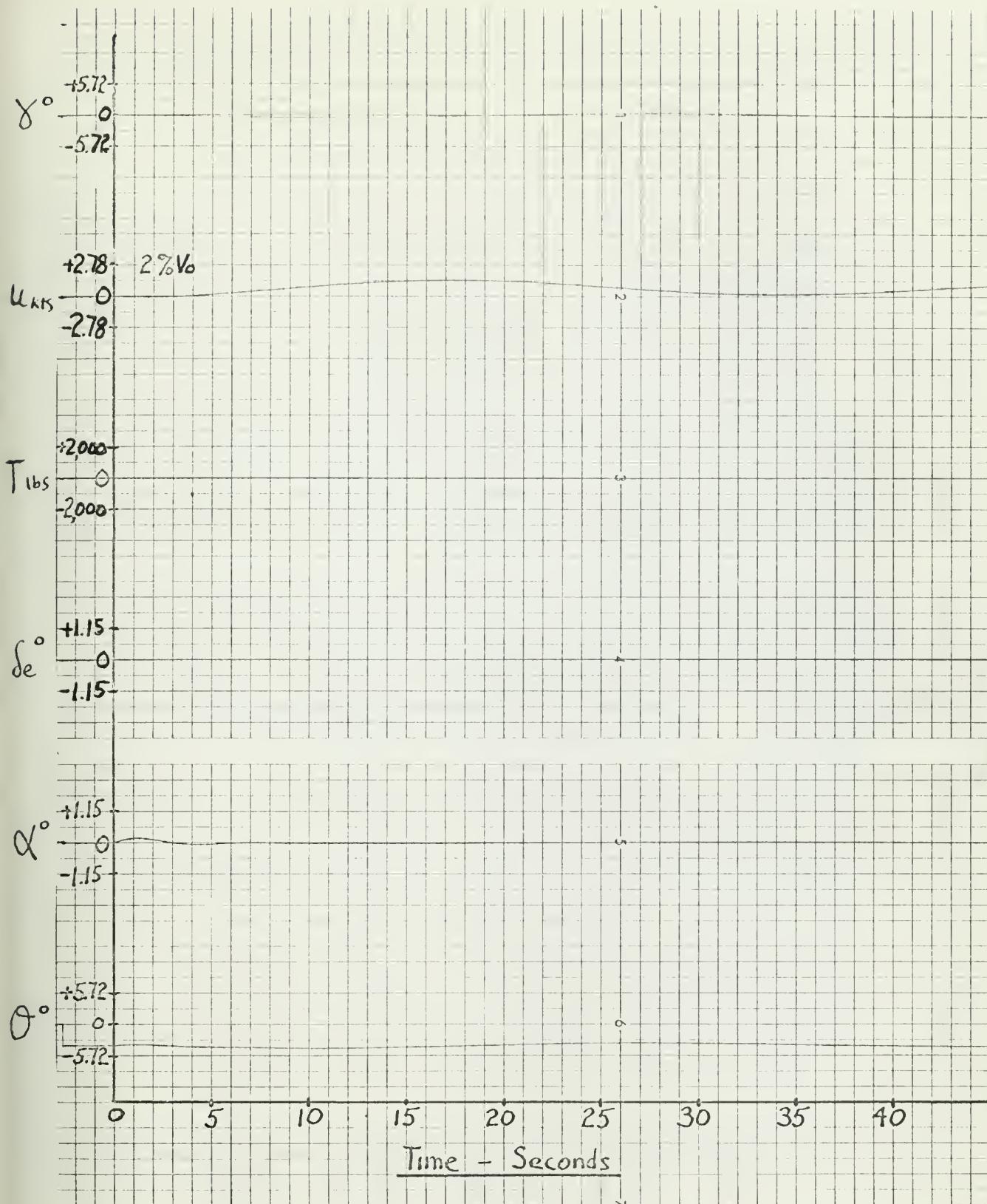


Fig. 19

Time History, 4° Step Input Pitch Angle, θ ,
Basic Airframe

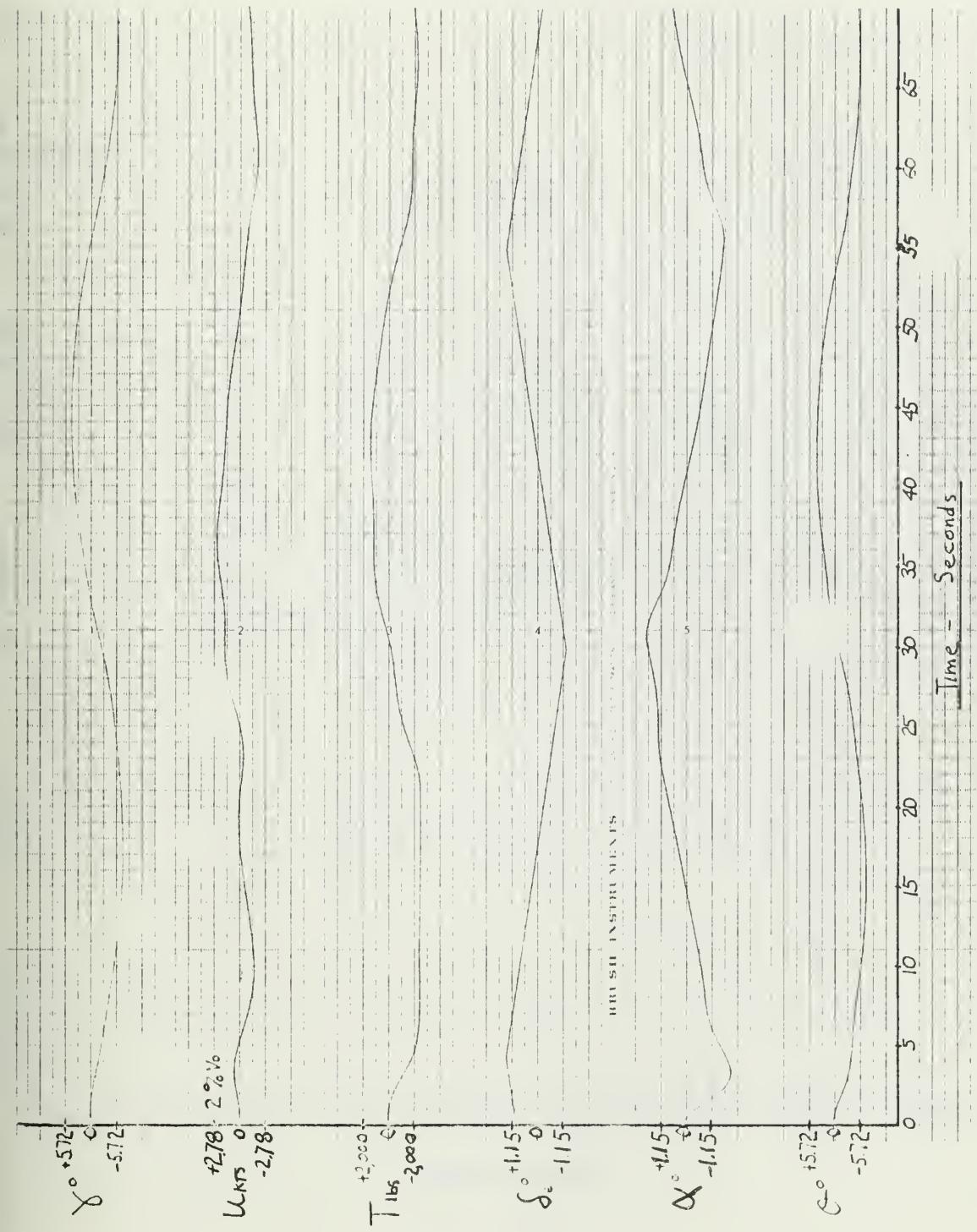


Fig. 20
Time History, .02 cps. Triangular 1.32° Elevator Deflection Input,
System 1-a

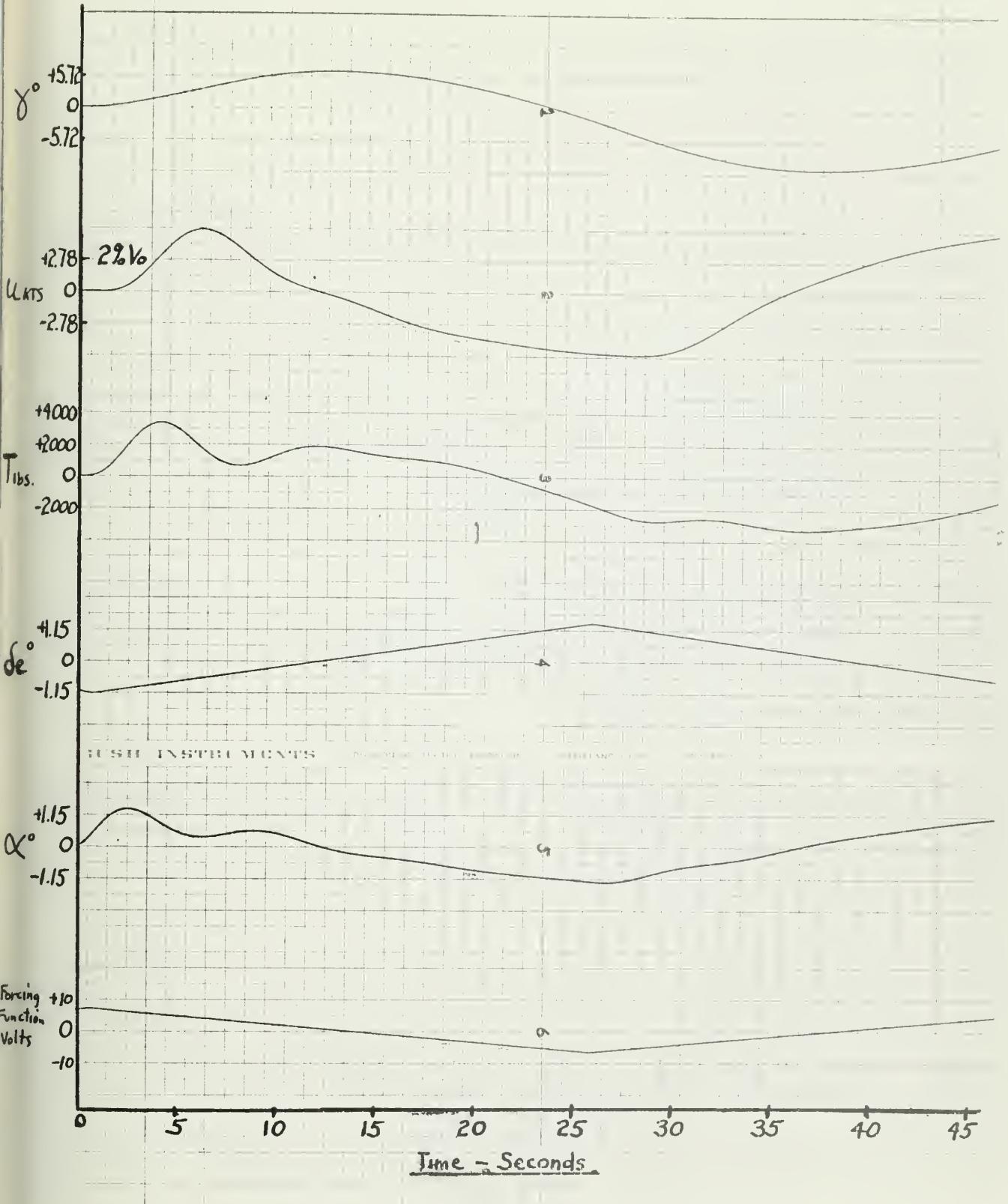


Fig. 21

Time History, .02 cps. Triangular 1.32° Elevator Deflection Input,
System 1-b.

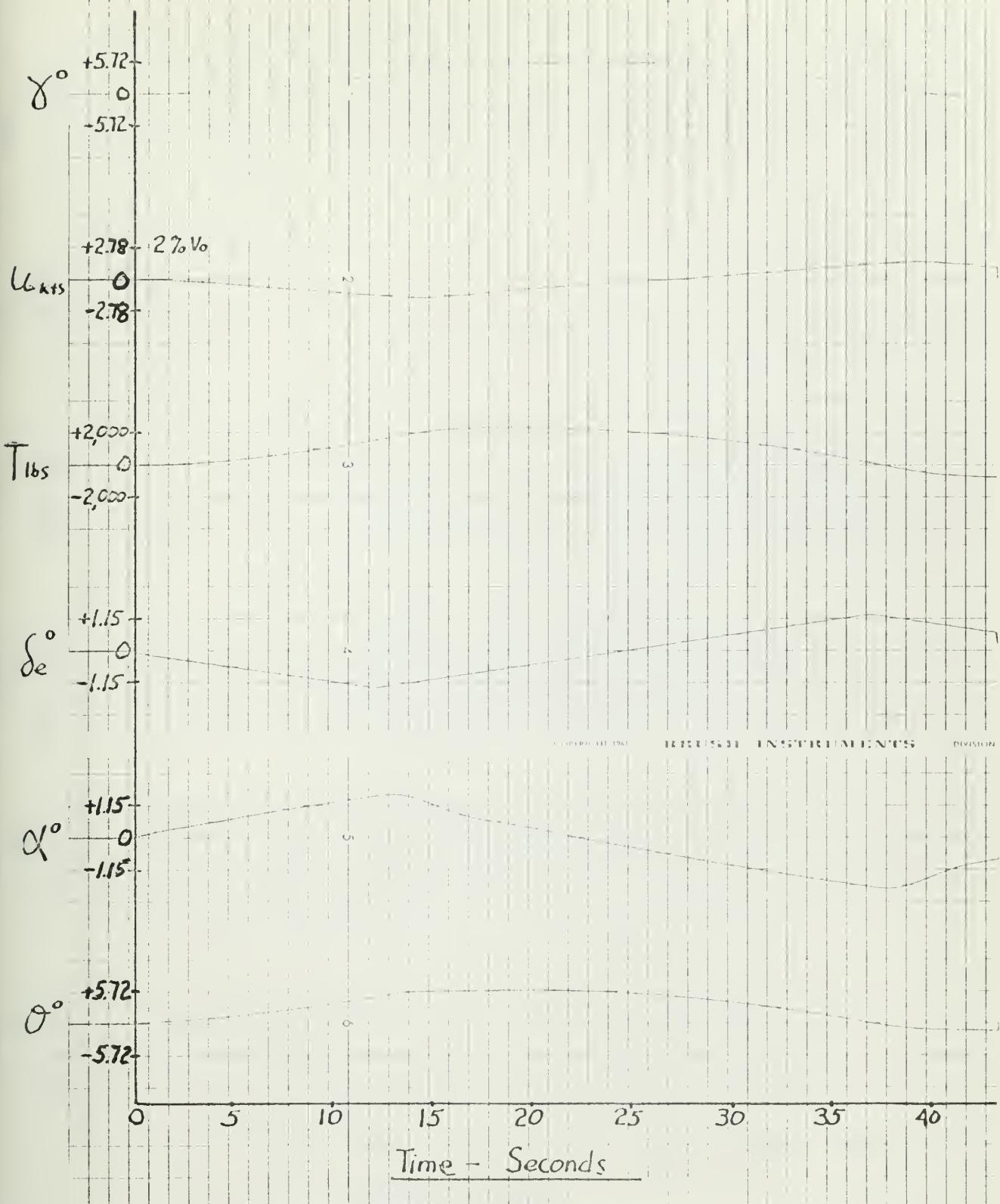


Fig. 22

Time History, .02 cps. Triangular 1.32°
Elevator Deflection Input, System 2

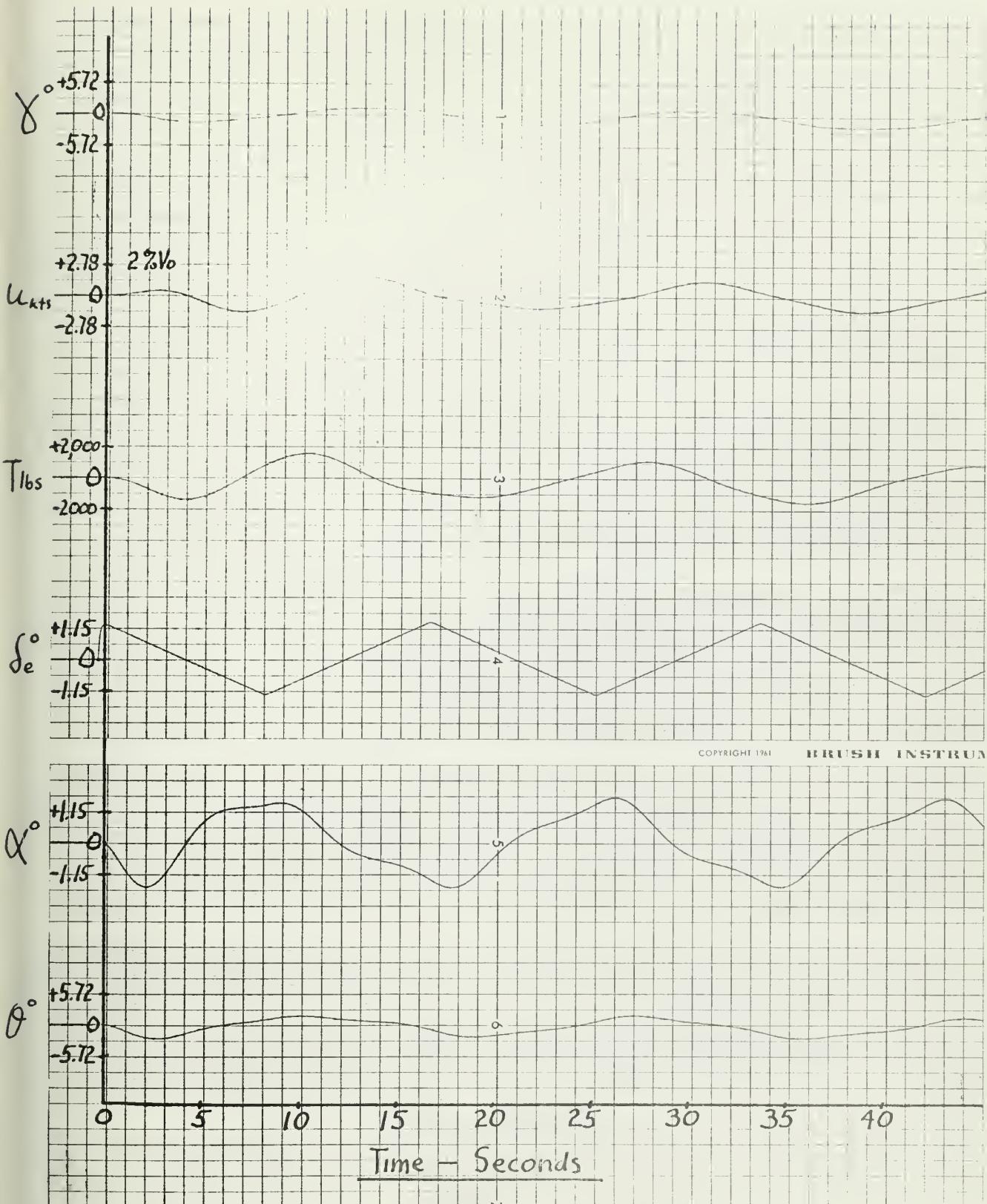


Fig. 23

Time History, .06 cps Triangular 1.32° Elevator
Deflection Input, System 1-a

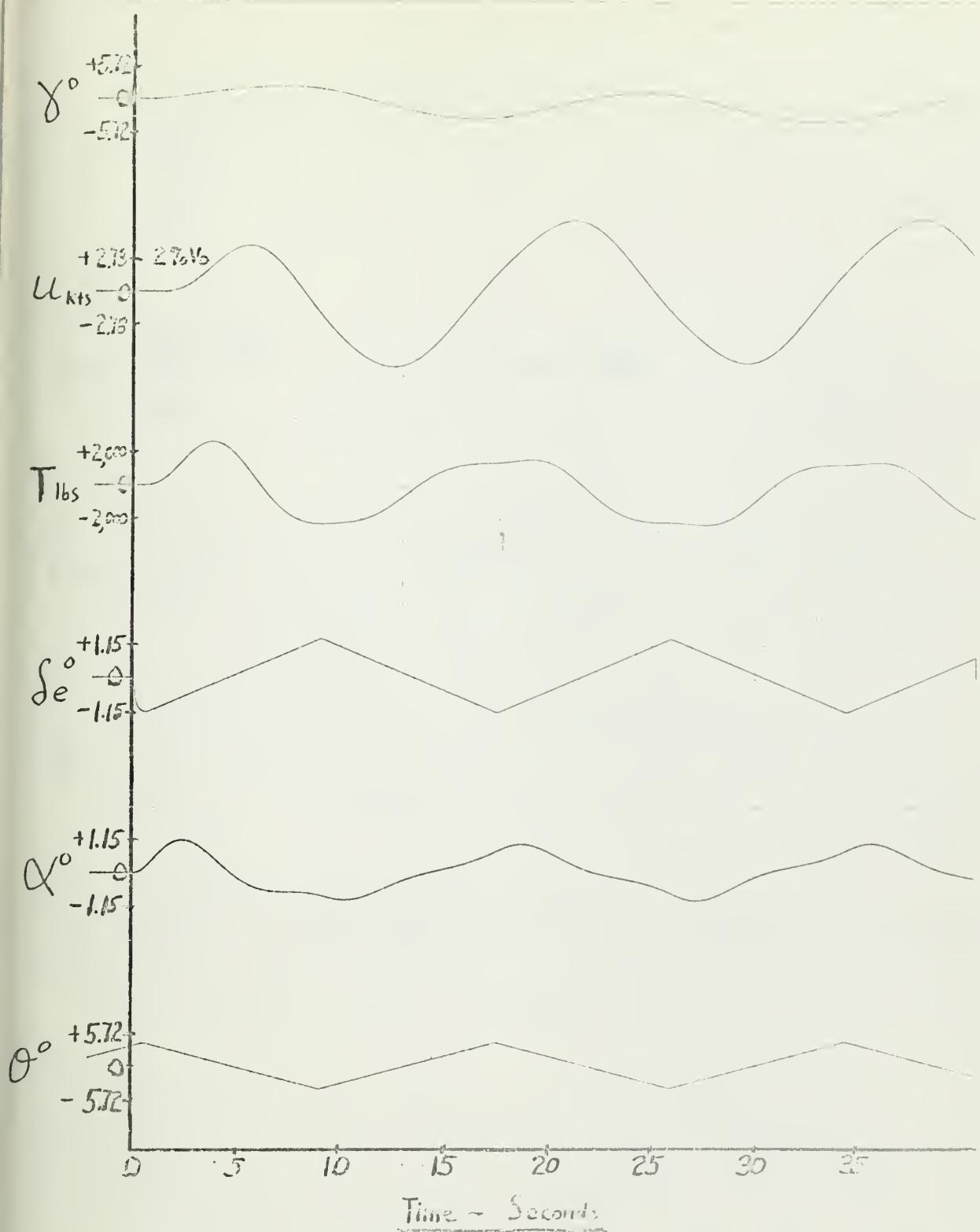


Fig. 24

Time History, .06 cps. Triangular 1.32° Heel
Deflection Input, Section 1-1

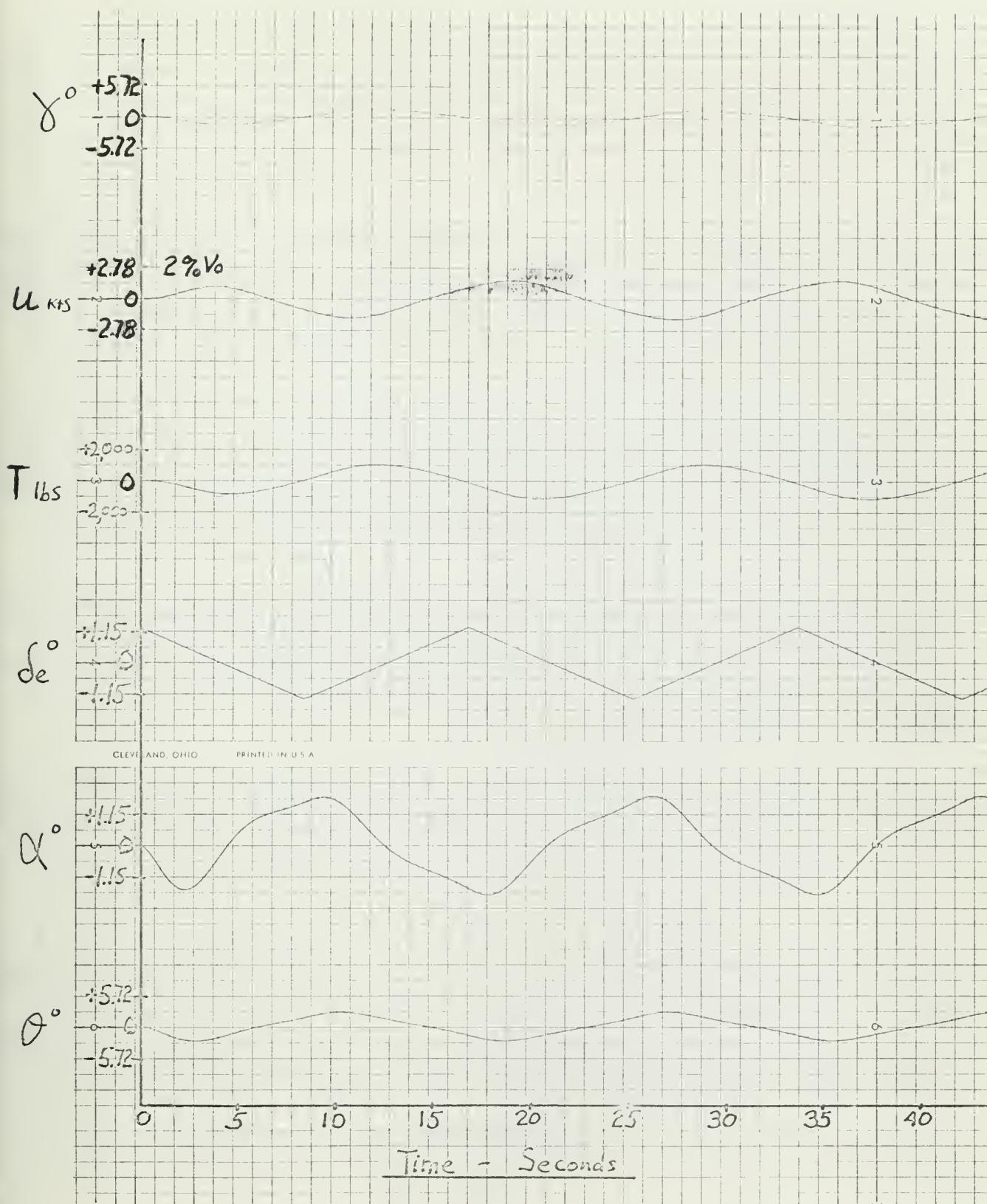


Fig. 25

Time History, .06 cps. Triangular 1.32° Elevator Deflection,
Input, System 2

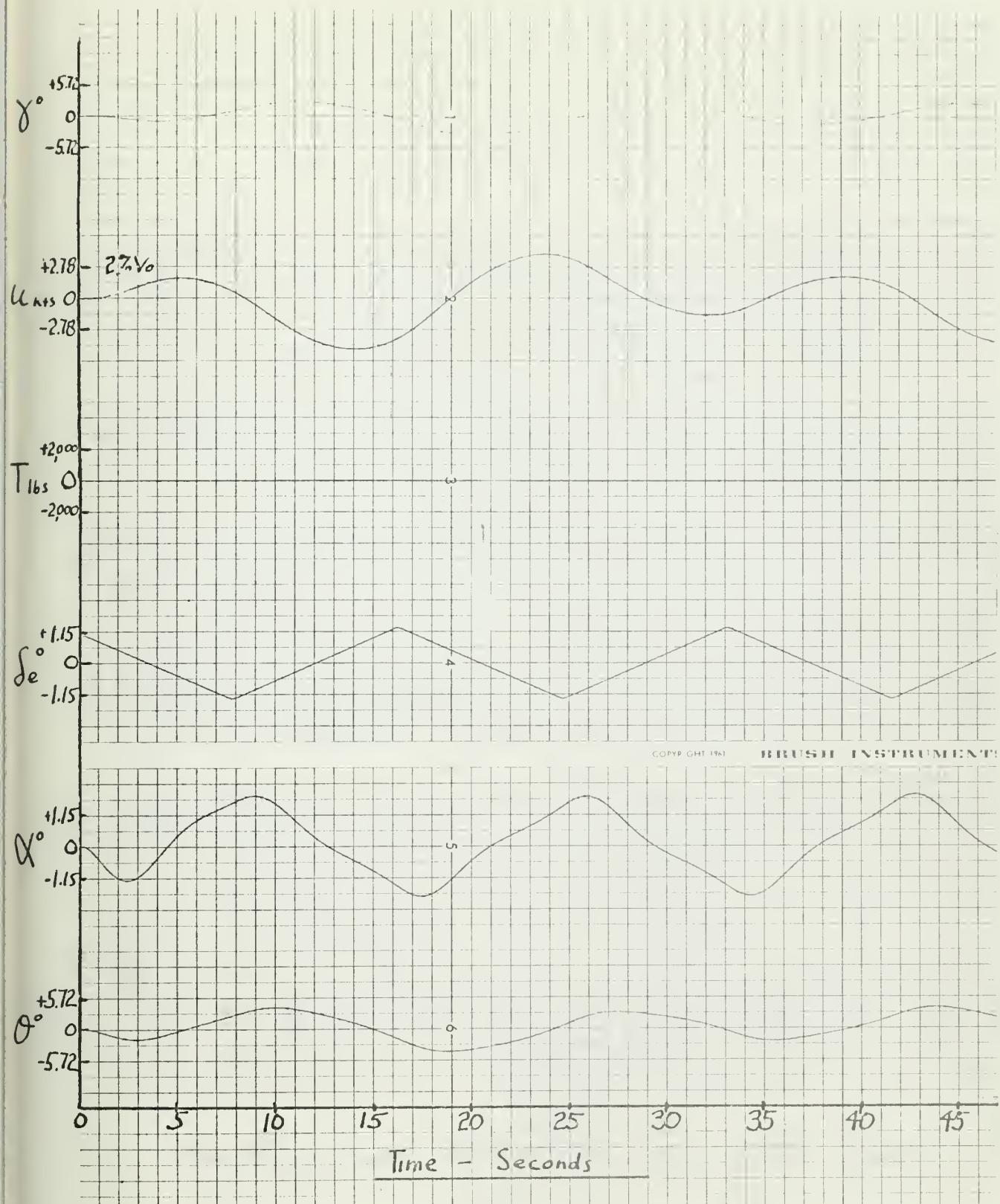


Fig. 26

Time History, .06 cps. Triangular 1.32° Elevator Deflection
Input, Basic Airframe

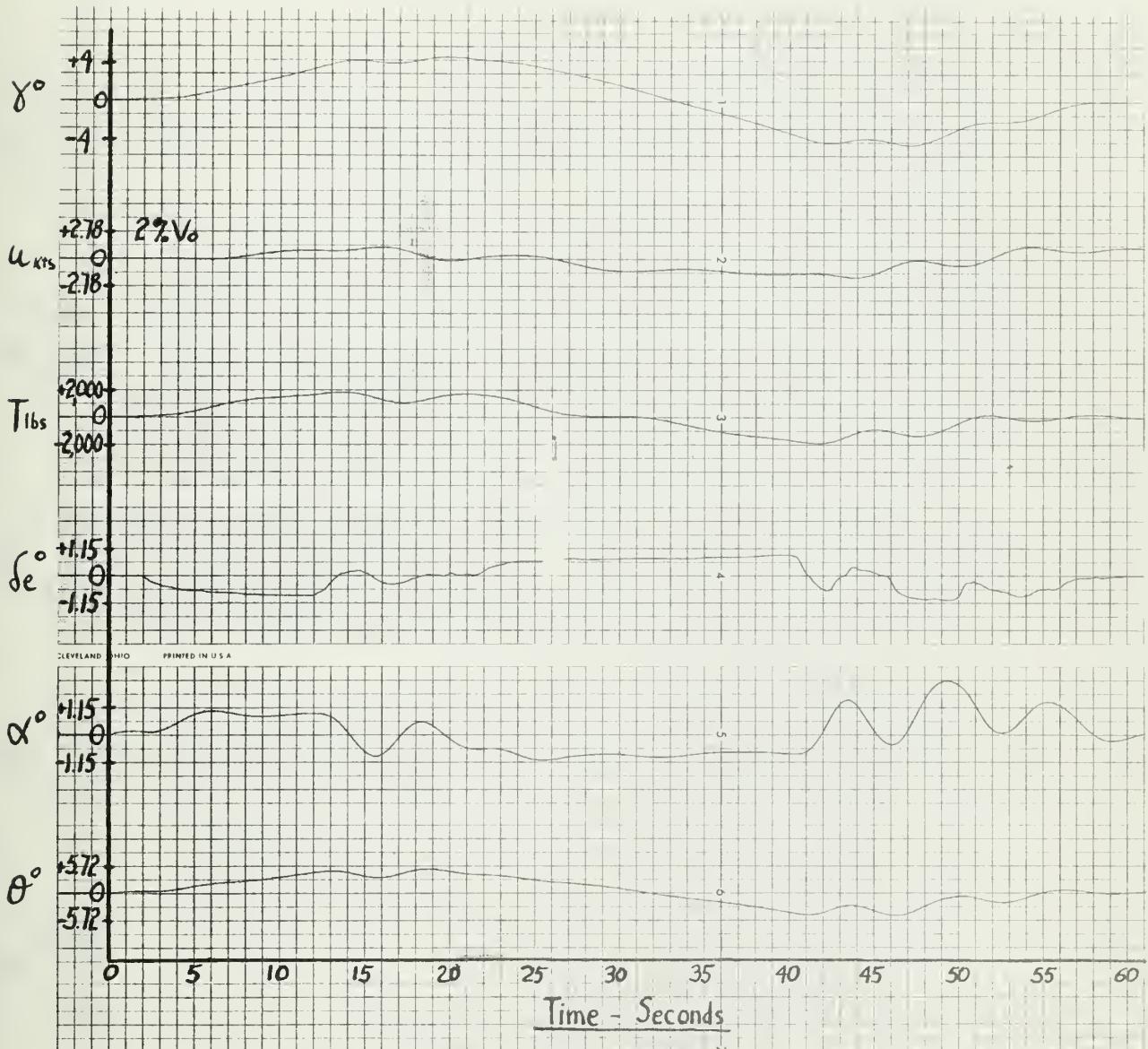


Fig. 27

Time History, Human Pilot Controlled Flight on Glide Slope,
System 1-a

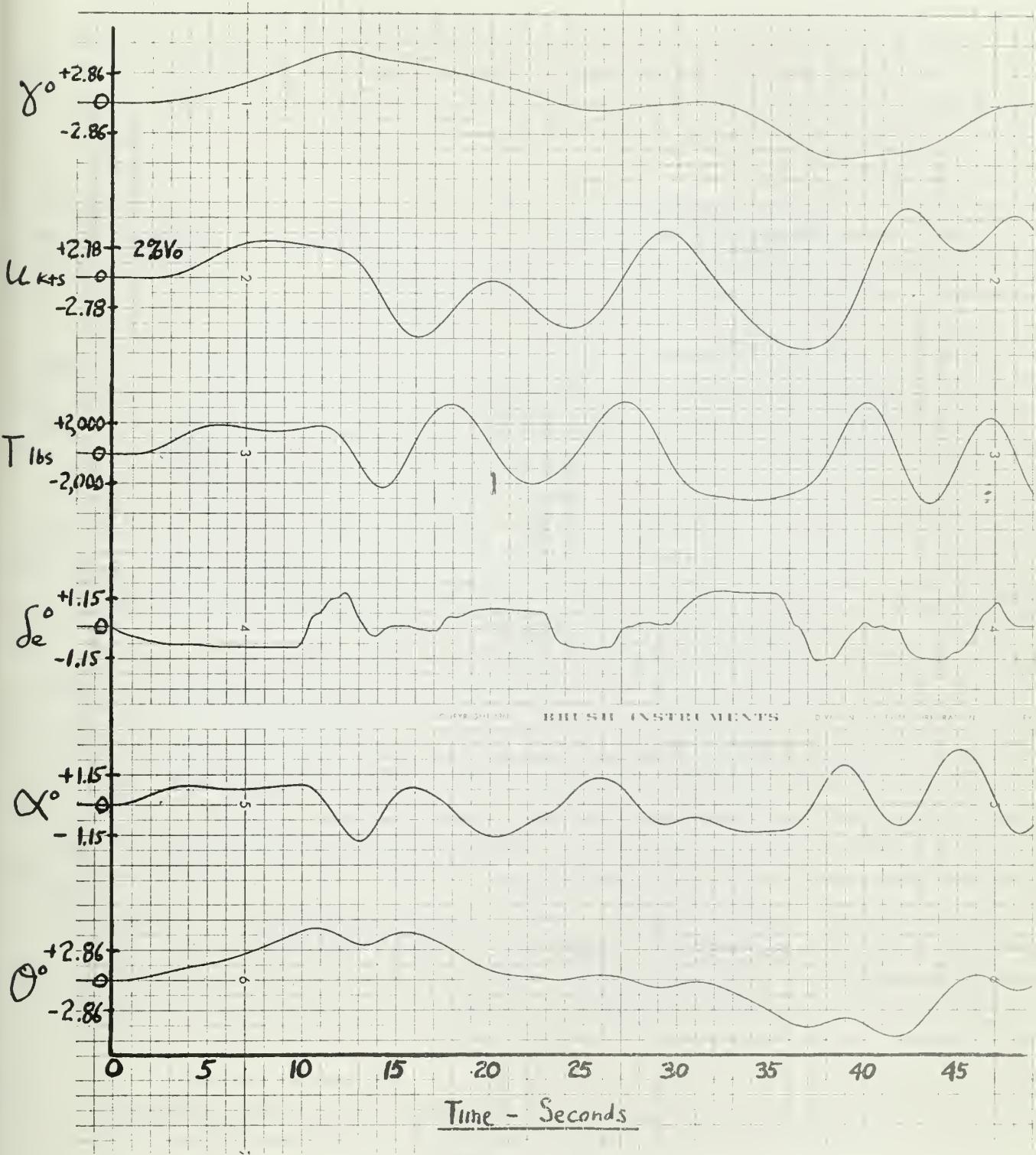


Fig. 28

Time History, Human Pilot Controlled Flight on Glide Slope,
System 1-b

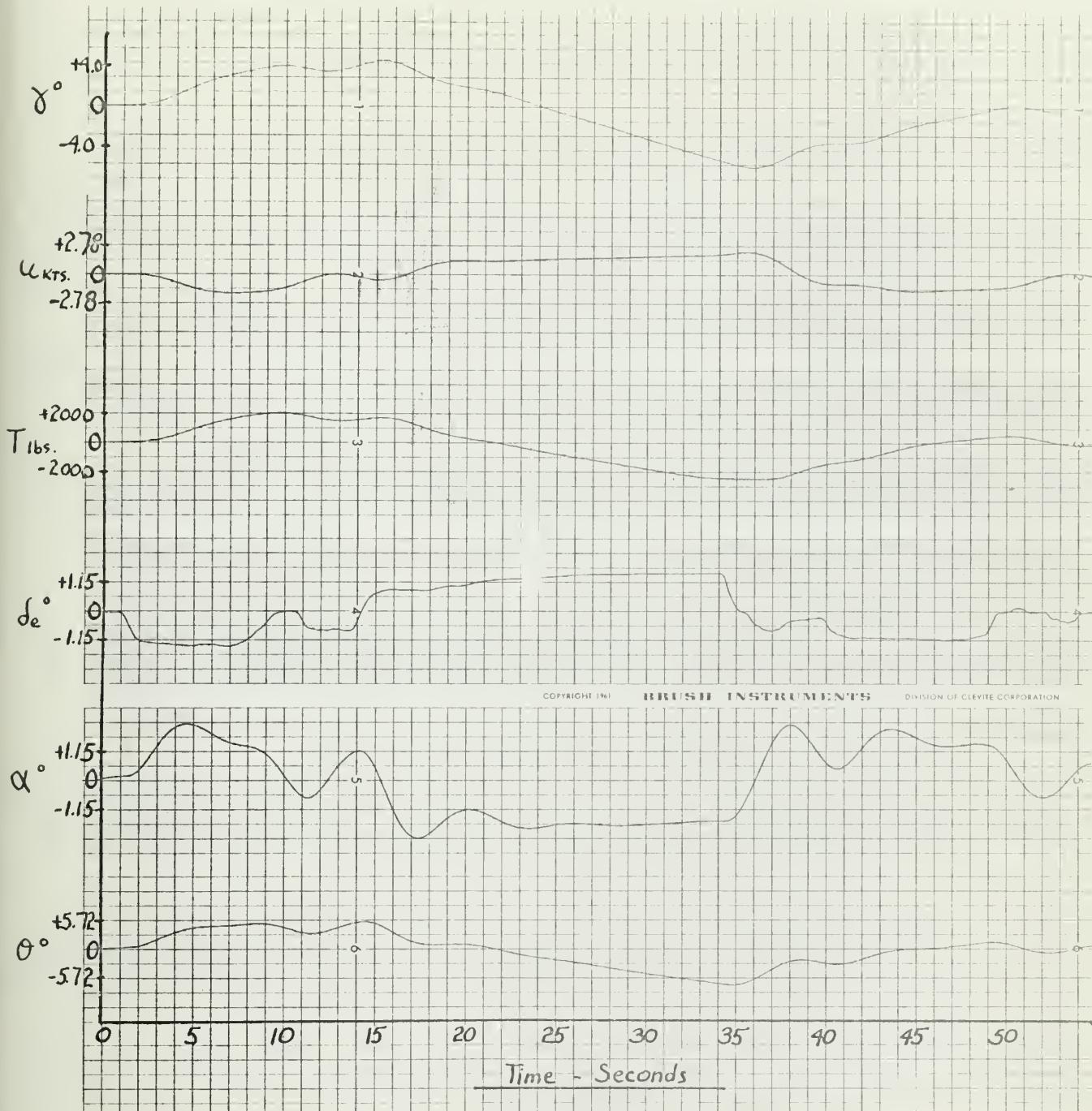


Fig. 29

Time History, Human Pilot Controlled Flight on Glide Slope,
System 2.

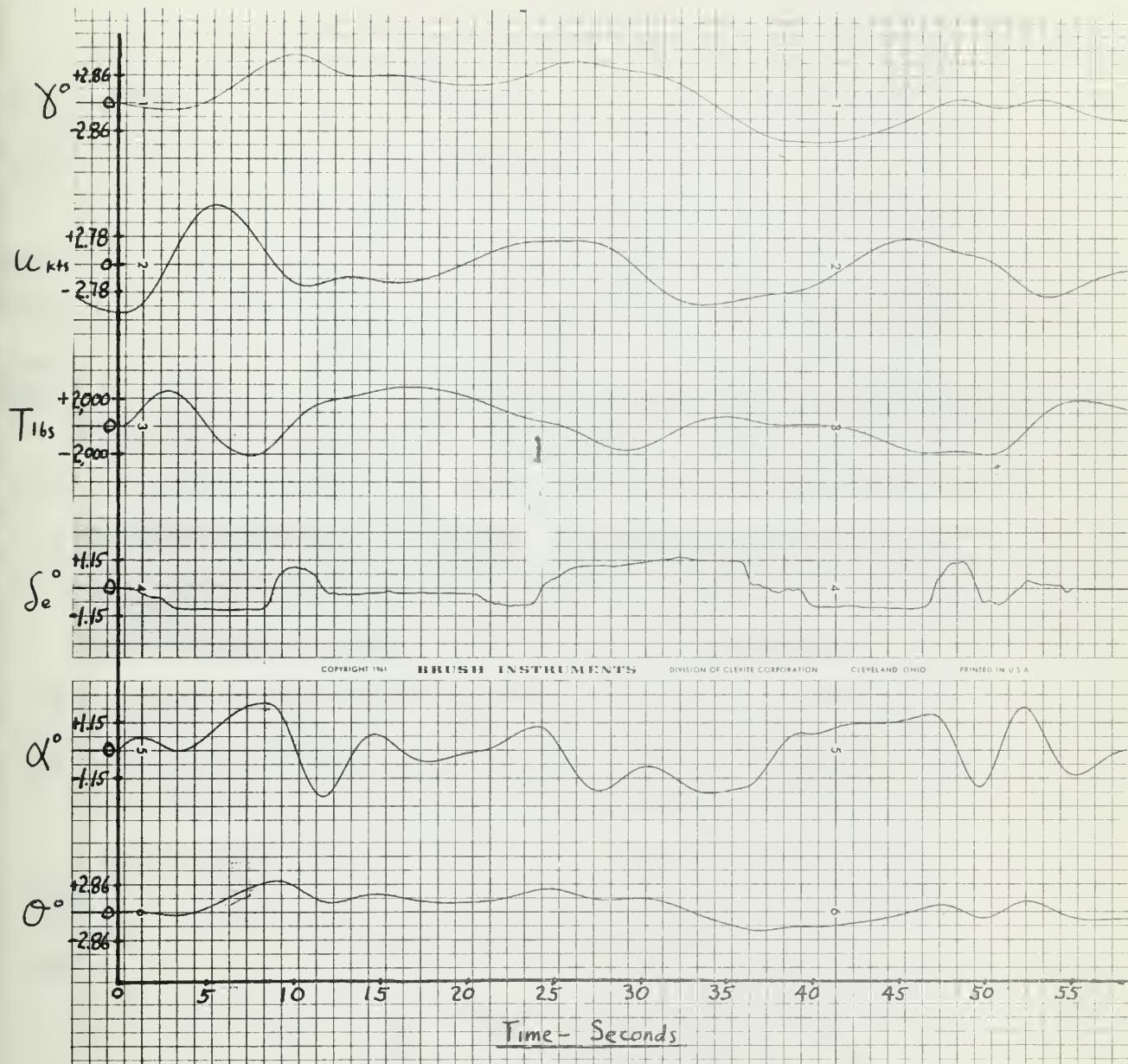


Fig. 30

Time History, Human Pilot Controlled Flight on Glide Slope, Sinusoidal Input of 5 Knots Horizontal Gust, System 1-a

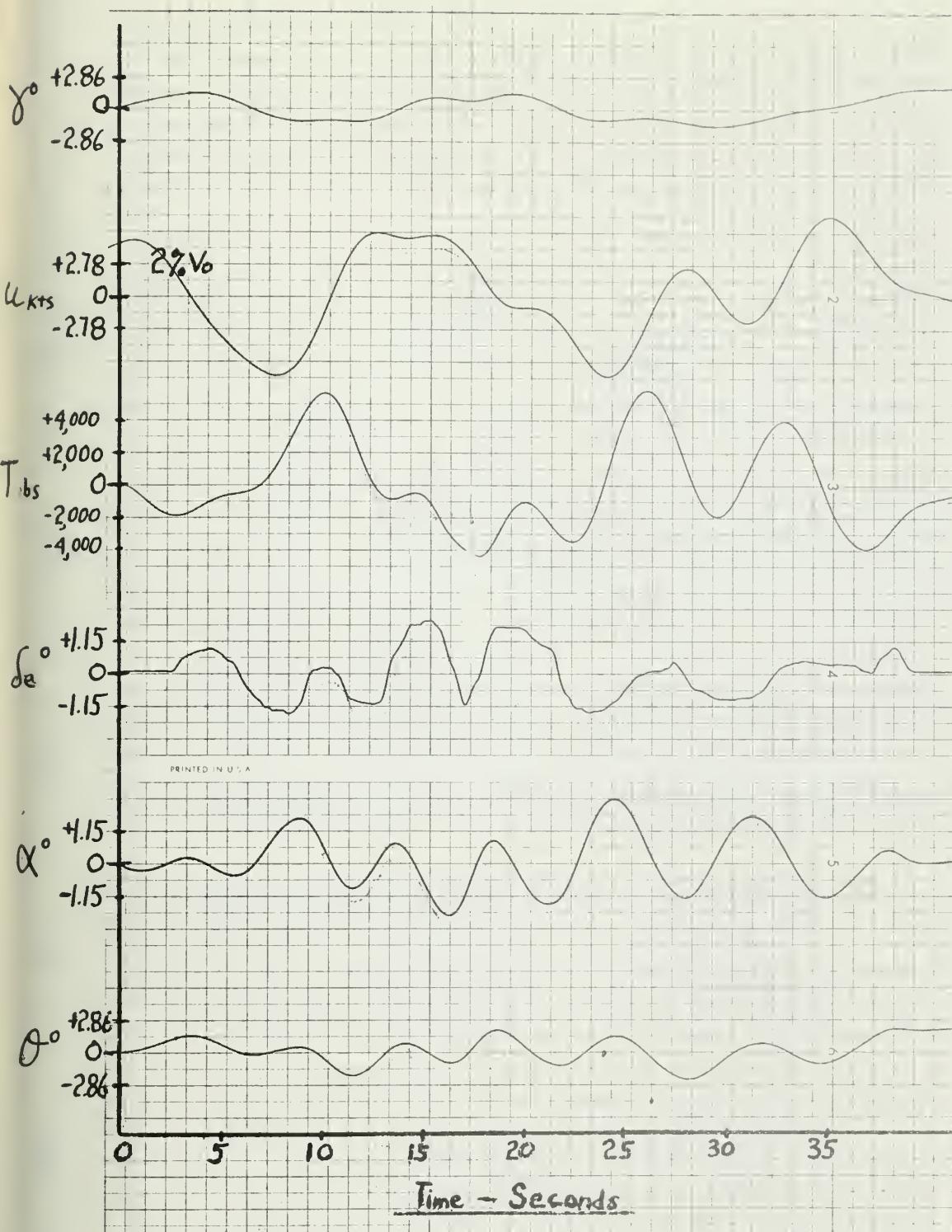


Fig. 31

Time History, Human Pilot Controlled Flight on Glide Slope,
Sinusoidal Input of 5 Knots Horizontal Gust, System 1-b

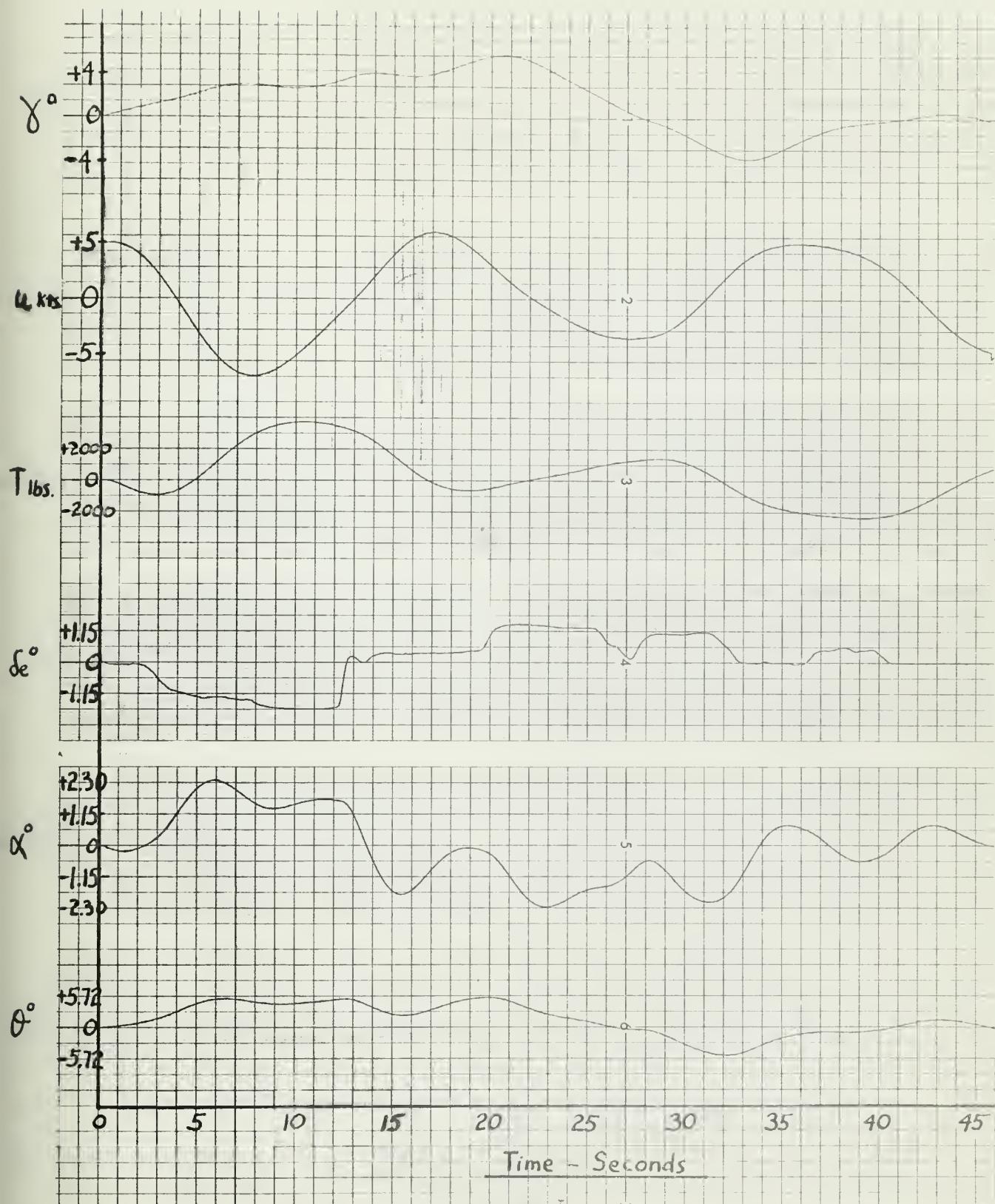


Fig. 32

Time History, Human Pilot Controlled Flight on Glide Slope,
Sinusoidal Input of 5 Knots Horizontal Gust, System 2.

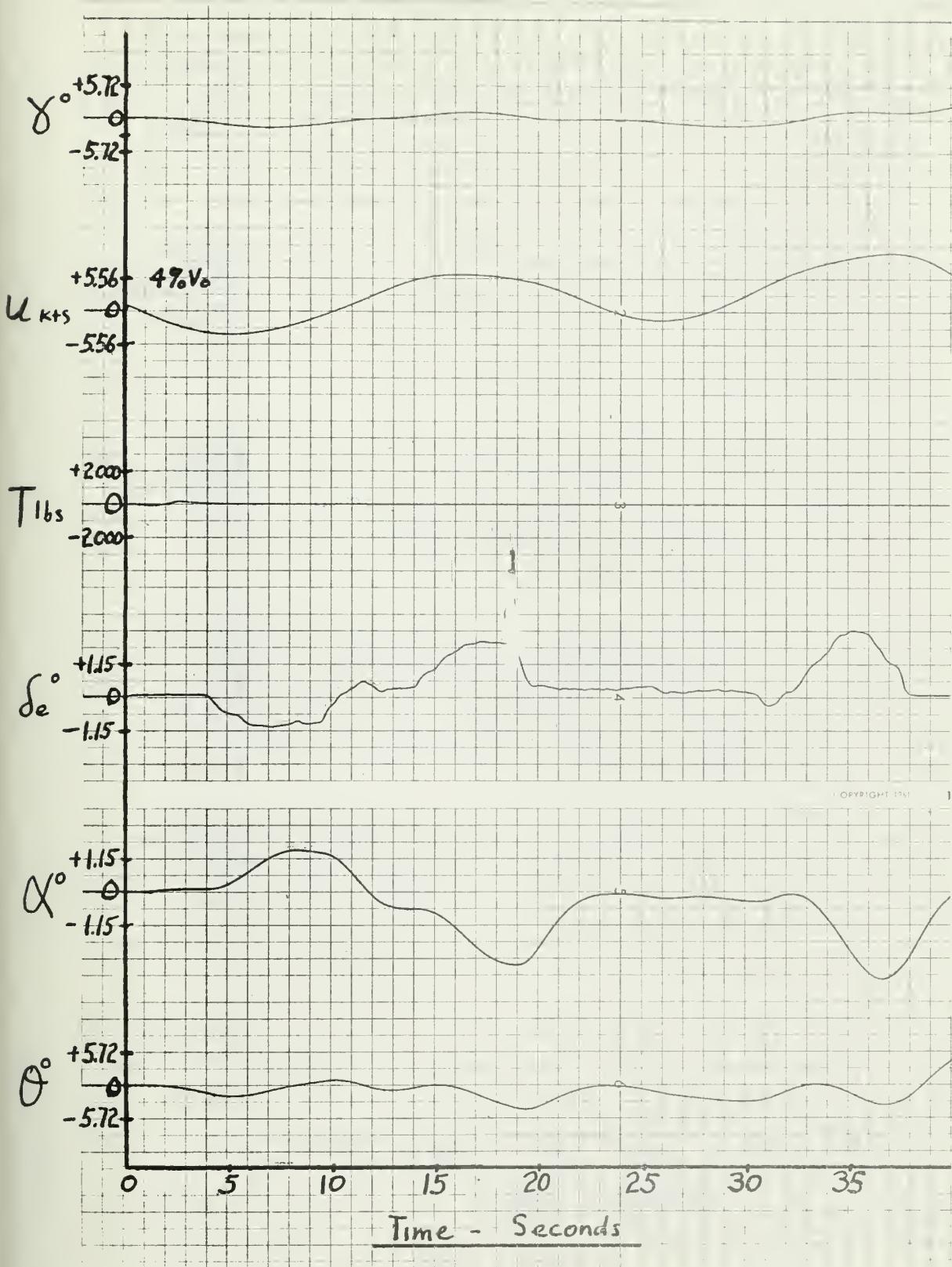


Fig. 33

Time History, Human Pilot Controlled Flight on Glide Slope,
Sinusoidal Input of 5 Knots Horizontal Gust, Without Auto-Throttle

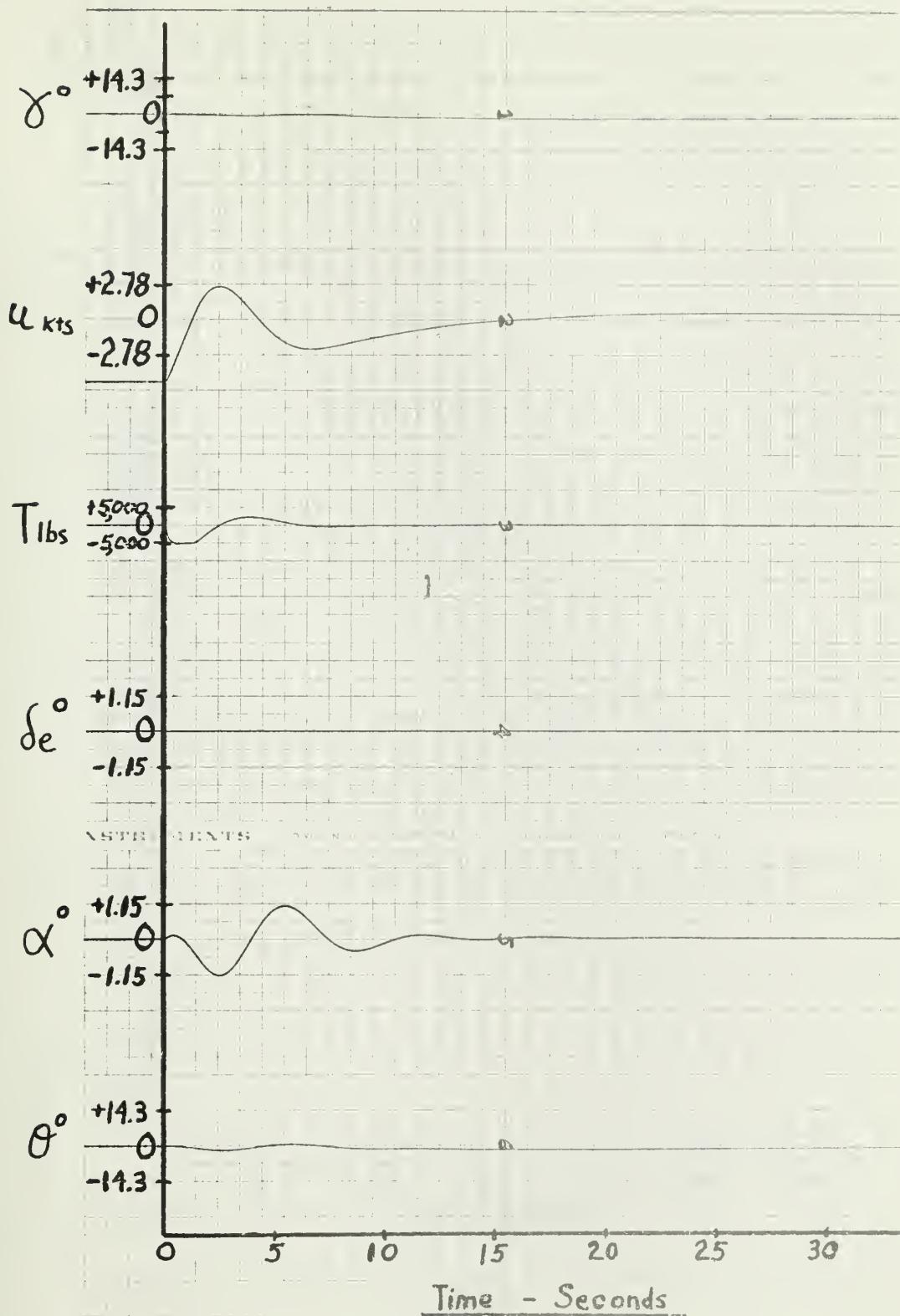


Fig. 34
Time History, 5° Knots Horizontal Gust Input,
Anti-Thrust System

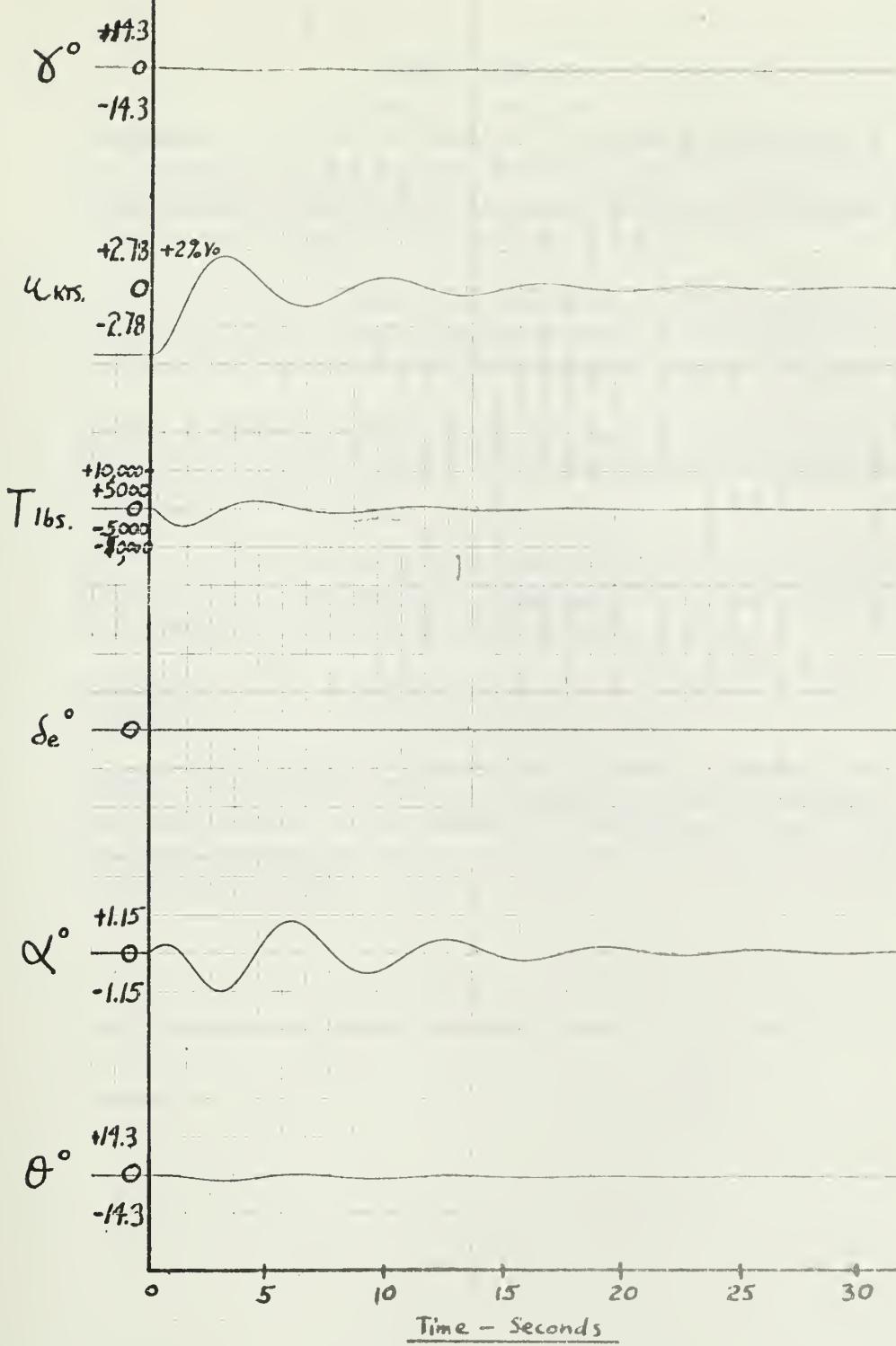


Fig. 35

Time History, 5 Knots Step Horizontal Gust Input, Anti-Thrust System with Changed Gain Constants

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APPENDIX I

Derivation of Transfer Functions

The dimensional derivatives shown in Table I were used to calculate the analytic transfer functions. Calculated values of these derivatives using F8 data, are shown in Table II.

The longitudinal Equations of Motion written in Matrix Laplace Form are (neglecting negligible terms);

$$\begin{pmatrix} s - X_u & -X_w & +g \\ -Z_u & s - Z_w & -sU_0 \\ -M_u & -(sM_w + M_w) & s^2 - M_g s \end{pmatrix} \begin{pmatrix} U(s) \\ W(s) \\ \Theta(s) \end{pmatrix} = \begin{pmatrix} 0 & X_{\Delta T} \\ Z_{\Delta e} & 0 \\ M_{\Delta e} & M_{\Delta T} \end{pmatrix} \begin{pmatrix} \Delta e \\ \Delta T \end{pmatrix}$$

The Transfer function $\left(\frac{U}{\Delta e}\right)$ Airframe then can be written as
(in determinant form):

$$\frac{\begin{vmatrix} 0 & -X_w & +g \\ Z_{\Delta e} & s - X_w & -sU_0 \\ M_{\Delta e} & -(sM_w + M_w) & s^2 - M_g s \end{vmatrix}}{D_1} = \frac{N_u}{D_1}$$

Where D_1 = determinant of homogeneous equations

$$\text{Expanded } D_1 = A s^4 + B s^3 + C s^2 + D s + E$$

Where $A = 1$

$$B = -(M_g + X_u + Z_w + U_0 M_w)$$

$$C = M_g Z_w - U_0 M_w + X_u (M_g + Z_w + U_0 M_w) - X_w Z_u$$

$$D = -X_u (M_g Z_w - U_0 M_w) - M_u U_0 X_w + M_g X_w Z_u + g (M_w Z_u + M_u)$$

$$E = g (M_w Z_u - M_u Z_w)$$

$$\text{Expanded } Nu = Bu \alpha^2 + Cu \alpha + Du$$

Where $Bu = Z_{se} X_w$

$$Cu = -Z_{se}(g M_w + M_g X_w) + M_{se}(U_0 X_w - g)$$

$$Du = g(M_{se} Z_w - M_w Z_{se})$$

Substituting values for these derivatives

$$\left(\frac{u}{\delta e}\right)_{\text{Airframe}} = \frac{.1971[4^2 + 4504 + 85.2]}{4^4 + .8654^3 + 11.5294^2 + .6964 + .416} = \frac{Nu}{D_1}$$

By a similar procedure,

$$\left(\frac{\theta}{\delta e}\right)_{\text{Airframe}} = \frac{-2.50[4^2 + .21554 + .00568]}{D_1}$$

(Positive elevator deflection is down)

The determinant for calculating $\left(\frac{u}{\Delta T}\right)_{\text{Airframe}}$ can be written as

$$\frac{\begin{vmatrix} X_{\Delta T} & -X_w & +g \\ 0 & 4 - Z_w & -4U_0 \\ M_{\Delta T} & -(4M_w + M_w) & 4^2 - M_g 4 \end{vmatrix}}{D_1}$$

Expanded:

$$\left(\frac{u}{\Delta T}\right)_{\text{Airframe}} = \frac{A_T 4^3 + B_T 4^2 + C_T 4 + D_T}{D_1}$$

Where

$$A_T = X_{\Delta T}$$

$$B_T = -X_{\Delta T}[Z_w + M_g] + U_0 M_w$$

$$C_T = X_{\Delta T}[Z_w M_g - U_0 M_w] + M_{\Delta T}[U_0 X_w - g]$$

$$D_T = M_{\Delta T} g Z_w$$

After substituting in values:

$$\left(\frac{u}{\Delta T}\right)_{\text{Airframe}} = \frac{.00145[4^3 + .80494^2 + 11.594 + .0430]}{D_1}$$

APPENDIX - I
 TABLE I-A
 LONGITUDINAL DIMENSIONAL STABILITY DERIVATIVE
 PARAMETERS
 (STABILITY AXIS SYSTEM)

QUANTITY	IN TERMS OF BASIC STABILITY DERIVATIVES			IN TERMS OF NON-DIMENSIONAL STABILITY DERIVATIVE PARAMETERS
	DIMENSIONAL		NON-DIMENSIONAL	
	DEFINITIONS	UNIT		
x_u	$\frac{1}{m} \frac{\partial X}{\partial u}$	$\frac{1}{sec}$	$-\frac{\rho S U}{m} (-C_D - C_{D_\alpha})$	$-\frac{1}{T} x_u$
x_w	$-\frac{1}{m} \frac{\partial X}{\partial w}$	$\frac{1}{sec}$	$-\frac{\rho S U}{2m} (C_L - C_{L_\alpha})$	$-\frac{1}{T} x_w$
x_{s_E}	$-\frac{1}{m} \frac{\partial X}{\partial s_E}$	$\frac{ft}{sec^2 rad}$	$-\frac{\rho S U^2}{2m} (-C_{D_{s_E}})$	$-\frac{U}{T} x_{s_E}$
z_u	$-\frac{1}{m} \frac{\partial Z}{\partial u}$	$\frac{1}{sec}$	$-\frac{\rho S U}{m} (-C_L - C_{L_u})$	$-\frac{1}{T} z_u$
z_w	$-\frac{1}{m} \frac{\partial Z}{\partial w}$	$\frac{1}{sec}$	$-\frac{\rho S U}{2m} (-C_{L_\alpha} - C_p)$	$-\frac{1}{T} z_w$
z_b	$-\frac{1}{m} \frac{\partial Z}{\partial q}$	$\frac{1}{l}$	$-\frac{\rho S c}{4m} (-C_{L_b})$	$-\frac{c}{T U} z_b$
z_q	$-\frac{1}{m} \frac{\partial Z}{\partial q}$	$\frac{ft}{sec \cdot rad}$	$-\frac{\rho S U c}{4m} (-C_{L_q})$	$-\frac{c}{T} z_q$
z_{s_E}	$-\frac{1}{m} \frac{\partial Z}{\partial s_E}$	$\frac{1}{sec^2 rad}$	$-\frac{\rho S U^2}{2m} (-C_{L_{s_E}})$	$-\frac{U}{T} z_{s_E}$
m_u	$-\frac{1}{I_y} \frac{\partial M}{\partial u}$	$\frac{1}{sec \cdot ft}$	$-\frac{\rho S U c}{I_y} (C_m + C_{m_u})$	$-\frac{2}{T C} m_u$
m_w	$-\frac{1}{I_y} \frac{\partial M}{\partial w}$	$\frac{1}{sec \cdot ft}$	$-\frac{\rho S U c}{2I_y} C_{m_\alpha}$	$-\frac{1}{T C} m_w$
m_b	$-\frac{1}{I_y} \frac{\partial M}{\partial q}$	$\frac{1}{ft}$	$-\frac{\rho S c^2}{4I_y} C_{m_b}$	$-\frac{1}{T U} m_b$
m_q	$-\frac{1}{I_y} \frac{\partial M}{\partial q}$	$\frac{1}{sec \cdot rad}$	$-\frac{\rho S U c^2}{4I_y} C_{m_q}$	$-\frac{1}{T} m_q$
m_{s_E}	$-\frac{1}{I_y} \frac{\partial M}{\partial s_E}$	$\frac{1}{sec^2 rad}$	$-\frac{\rho S U^2 c}{2I_y} C_{m_{s_E}}$	$-\frac{U}{T C} m_{s_E}$

APPENDIX - I

TABLE I-B

LONGITUDINAL NON-DIMENSIONAL STABILITY DERIVATIVES
(STABILITY AXIS SYSTEM)

BASIC NON-DIMENSIONAL STABILITY DERIVATIVES		NON-DIMENSIONAL STABILITY DERIVATIVE PARAMETERS
TOTAL AIRFRAME	THEORETICAL HORIZONTAL TAIL CONTRIBUTION	
DEFINITIONS	UNIT	
$C_D = \frac{D_{\text{drag}}}{qS}$	$\frac{1}{1}$	
$C_{D_u} = \frac{U}{2} \frac{\partial C_D}{\partial U}$	$\frac{1}{1}$	$x_u = (-C_D - C_{D_u})$
$C_{D_\alpha} = \frac{\partial C_D}{\partial \alpha}$	$\frac{1}{\text{rad}}$	$x_\alpha = \frac{1}{2} (C_L - C_{D_\alpha})$
$C_{D_{\delta_E}} = \frac{\partial C_D}{\partial \delta_E}$	$\frac{1}{\text{rad}}$	$x_{\delta_E} = -\frac{1}{2} C_{D_{\delta_E}}$
$C_L = \frac{L_{\text{lift}}}{qS}$	$\frac{1}{1}$	
$C_{L_u} = \frac{U}{2} \frac{\partial C_L}{\partial U}$	$\frac{1}{1}$	$x_u = (-C_L - C_{L_u})$
$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$	$\frac{1}{\text{rad}}$	$x_\alpha = \frac{1}{2} (-C_{L_\alpha} - C_D)$
$C_{L_{\dot{\alpha}}} = \frac{\partial C_L}{\partial (\dot{\alpha}c)}$	$\frac{1}{\text{rad}}$	$x_{\dot{\alpha}} = -\frac{1}{4} C_{L_{\dot{\alpha}}}$
$C_{L_q} = \frac{\partial C_L}{\partial (qc)}$	$\frac{1}{\text{rad}}$	$x_q = -\frac{1}{4} C_{L_q}$
$C_{L_{\delta_E}} = \frac{\partial C_L}{\partial \delta_E}$	$\frac{1}{\text{rad}}$	$x_{\delta_E} = -\frac{1}{2} C_{L_{\delta_E}}$
$C_m = \frac{M}{qS c}$	$\frac{1}{1}$	
$C_{m_u} = \frac{U}{2} \frac{\partial C_m}{\partial U}$	$\frac{1}{1}$	$m_u = \frac{1}{2} \left(\frac{c}{k_y} \right)^2 (C_m + C_{m_u})$
$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$	$\frac{1}{\text{rad}}$	$m_\alpha = \frac{1}{2} \left(\frac{c}{k_y} \right)^2 C_{m_\alpha}$
$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial (\dot{\alpha}c)}$	$\frac{1}{\text{rad}}$	$m_{\dot{\alpha}} = \frac{1}{4} \left(\frac{c}{k_y} \right)^2 C_{m_{\dot{\alpha}}}$
$C_{m_q} = \frac{\partial C_m}{\partial (qc)}$	$\frac{1}{\text{rad}}$	$m_q = \frac{1}{4} \left(\frac{c}{k_y} \right)^2 C_{m_q}$
$C_{m_{\delta_E}} = \frac{\partial C_m}{\partial \delta_E}$	$\frac{1}{\text{rad}}$	$m_{\delta_E} = \frac{1}{2} \left(\frac{c}{k_y} \right)^2 C_{m_{\delta_E}}$

Appendix I Table II

Dimensional Stability Derivatives

$$M_g = \frac{\rho U S C^2 C_{mg}}{4 I_{yy}} = \frac{2.08 (11.78)^2 (-4.5)}{4 (96,000)} = -0.338 \frac{1}{\text{sec}^2 \text{rad}}$$

$$M_w = \frac{\rho S C^2}{4 I_{yy}} C_{m\alpha} = \frac{(2.378 \cdot 10^3)(375)(11.78)(-0.55)}{(4)(96,000)} = -0.0001766 \frac{1}{\text{ft}}$$

$$M_w = \frac{\rho U S C}{2 I_{yy}} C_{m\alpha} = \frac{(208)(11.78)(-0.380)}{(2)(96,000)} = -0.0485 \frac{1}{\text{sec} \cdot \text{ft}}$$

$$M_v = \frac{\rho U S C}{I_{yy}} (C_{mu} + C_m) = \frac{(208)(11.78)(0.0074)}{96,000} = 0.000189 \frac{1}{\text{sec} \cdot \text{ft}}$$

$$Z_w = \frac{\rho U S}{2 m} (-C_{Lx} - C_D) = \frac{(208)}{2(683)} (-2.598 - 1.197) = -0.426 \frac{1}{\text{sec}}$$

$$Z_u = \frac{\rho U S}{m} (-C_{Lu} - C_L) = \frac{(208)}{683} (-0.870) = -0.265 \frac{1}{\text{sec}}$$

$$X_u = \frac{\rho U S}{m} (-C_{Dv} - C_D) = \frac{208}{683} (-0.197) = -0.060 \frac{1}{\text{sec}}$$

$$X_w = \frac{\rho U S}{2 m} (C_L - C_{D\alpha}) = \frac{208}{2(683)} (0.870 - 0.963) = -0.01415 \frac{1}{\text{sec}}$$

$$C_m = -C_T \frac{\partial T}{C} = \frac{(-0.195)(-0.437)}{11.78} = 0.00723$$

$$Z_{se} = \frac{\rho U^2 S}{2 m} C_{Lse} = \frac{(65.105)(375)(0.3897)}{683} = -13.94 \frac{1}{\text{sec}^2 \text{rad}}$$

$$M_{se} = \frac{\rho U^2 S C}{2 I_{yy}} C_{mse} = \frac{(65.1)(375)(11.78)(-0.835)}{(96,000)} = -2.50 \frac{1}{\text{sec}^2 \text{rad}}$$

$$X_{\Delta T} = \frac{\cos(\delta + \gamma_0)}{m} = 0.00145 \frac{\text{ft}}{\text{sec}^2 \text{lb}}$$

$$M_{\Delta T} = -\frac{Z_j}{I_{yy}} = -4.55 \times 10^{-6} \frac{1}{\text{sec}^2 \text{lb}}$$

APPENDIX II

DYNAMIC STABILITY FORTRAN PROGRAM

Longitudinal - Program LONGSTAB

This program, once entered with required airplane parameters, computes the longitudinal stick fixed and/or stick free (when pertinent) stability derivatives, and the corresponding stability equation coefficients. It then solves these equations for roots, periods, and times to damp to 1/2 amplitude for both the phugoid and short period modes. In addition the value of Routh's discriminant is determined. The sequence of computations can be repeated for as many different flight regimes as desired.

There are a total of five data cards required for the stick-fixed only solutions, with an additional two cards required for a stick-free solution. Thus for a combination stick-fixed and free solution, there will be a total of seven data cards required for each flight regime desired.

The initial data card controls the types of solutions desired (stick-fixed, free, or both), and the number of consecutive runs to be made. A list of program symbols with their meanings appear in Table I to this Appendix.

The second card contains an alpha-numeric run identification or an arbitrary title.

The third card is the first of the general input data cards. This card should have entered on it:

S_t (tail area), S_w (wing area), $C_{L\alpha}$, γ tail, S_B (body area), l_B (body length), ρ , g (acceleration).

The parameters are entered eight to a card, each being allowed 10 columns. There are 80 columns on each card. Each parameter may be entered anywhere in its assigned ten columns, but must have a decimal point included in it. This same format is followed for each of the succeeding cards.

The fourth card should have the following aircraft parameters entered on it:

W (aircraft weight, lbs.); $\frac{\partial \dot{E}}{\partial \alpha}$; θ_0 in degrees; h , (distance from c.g. to thrust line, ft.); C_t (coefficient of thrust); C_m ; I_{YY} (slug ft.²); V (forward velocity ft./sec.).

The fifth card should have the following:

C_D ; $C_{L\alpha}$; cTA ; $C_{L\text{wing}}$; c (wing chord); l_t (c.g. to a.c. tail, ft.); $X_{\text{c.g.}}$ (x distance of c.g., ft.); X_{AC} (x distance of wing a.c. in ft.).

Cards 2 through 5 are repeated for each different run, stick fixed. If it is desired to compute a stick free solution simultaneously, then two additional data cards (6 and 7) are required for each run.

Card 6 contains the following parameters:

C_T (tail chord, ft.); K_e^2 (radius of gyration, squared); μ_e ; B_1 ; B_2 ; B'_2 ; z_γ ; z_i .

Card 7 contains the following parameters:

m_γ ; m_i ; m_e (mass elevator, slugs); S_e (area elevator, ft.²).

Thus for one aircraft flight regime (say Sea Level, Mach 0.6), for both stick fixed and free, there would be required data cards 1 through 7. For each succeeding run, cards 2 through 7 would have to be repeated with the new parameters entered. Card one would have to be suitably prepared to reflect the total number of runs and mode of runs desired. See Fig. 1 this Appendix for sample data cards. Note the first card is of format 13 for the number of runs, and 11 for mode of operation. All other data cards are of 8F10.0 format (each card holds 8 fields of 10 columns, each, one data number to be entered per field, in floating point format; i.e., with a decimal point somewhere in the number.)

The program prints out the calculated stability derivatives as well as the computed solutions to equations.

TABLE I
PROGRAM SYMBOLS AND MEANINGS
Program LONGSTAB

<u>Program mnemonic</u>	<u>Meaning</u>
NOS	Number of runs to be made. I3 format. card 1
MODE	Decision stick fixed (1), or stick free (2). I1. card 1
ST	S_t , tail area. card 3.
SW	S_w , wing area. card 3.
CLALFAT	$C_{L_{XT}}$, Tail lift curve slope. card 3.
ETATAIL	η_T , Tail efficiency, C_L/C_L . card 3.
SB	S_B , Body area card 3.
BL	l_B , Body length card 3.
RHO	ρ , Atmospheric density, card 3.
G	g , Acceleration due to gravity. card 3.
W	w, aircraft weight. card 4.
EPSALFA	$\frac{\partial \epsilon}{\partial \alpha}$ card 4.
THETA1	θ_0 , initial angle of pitch, degrees. card 4.
YH	h, distance from c.g. to thrust line. card 4.
CT	C_t , coefficient of thrust. card 4.
CMALFA	$C_{m\alpha}$, per radian. card 4.
YI	I_{yy} , moment of inertia. card 4.
V	V, forward velocity, ft./sec. card 4.
CSUBD	C_D , coefficient of drag. card 5.

CLALFA $C_{L\alpha}$, winglift curve slope. card 5.
 EPIA $\epsilon\pi A$, card 5.
 CSUBL C_L wing, card 5.
 C c, wing chord. card 5.
 TL l_t , c.g. to a.c. tail. card 5.
 XCG $x_{c.g.}$, x distance of c.g. card 5.
 XAC $x_{a.c.}$, x distance of wing a.c. card 5.
 CTAIL C_t , Tail chord. card 6.
 XKE k_e^2 , radius of gyration squared. card 6.
 UE μ_e , relative elevator density. card 6.
 B1 $B_1, C_{h\alpha_T}$. card 6.
 B2 $B_2, C_{h\delta_e}$. card 6.
 B2PRIME $B_2, 1/2 C_{h\dot{\delta}_e}$. card 6.
 ZETA ζ , card 6.
 ZETADOT $\dot{\zeta}$, card 6.
 AMETA m_ζ , card 7.
 AMETADT $m_{\dot{\zeta}}$, card 7.
 XME m_e , mass elevator. card 7.
 SE S_e , area elevator. card 7.

Fig. 1

Sample Data Cards

LONGSTAB

0032
NOS

Longstab Data 1 control card

II - Fig. 1 continued

12230.0 0.50 0.0 -.4514 .01928 -.67614 16000.0 670.14
w $\frac{\partial \epsilon}{\partial \alpha}$ θ_0 h C_T C_{MD} T_{yy} v

LONGSTAB DATA 4

① 0.01838 4.350 11.85 .0669 8.68 22.05 1.969 2.17
 C_D C_{L_w} ρ_{TA} C_{L_w} C l_t $X_{c.g.}$ $X_{2.c.}$

LONG-STAB DATA 3

C_F (he^2/m_e) B_1 B_2 B_2' $3n$ $3n$

LONGSTAB DATA 6

- Fig. 2. -

-1525 -0744 3.0 14.8

Dmn Smj. me Se

LONGSTAB DATA 7

Fortran Program LONGSTAB

```

:::JOB PELL*LCNGSTAB 1.5 MINUTES
      PROGRAM LONGSTAB
      PROGRAM FOR THE COMPUTATION OF THE ROOTS OF THE CHARACTERISTIC
      DYNAMIC LONGITUDINAL STABILITY (STICK FIXED) EQUATIONS
      DIMENSION KAPPA(10),CPR(129),CPI(129),ROOTR(128),ROOTI(128)
      DIMENSION CRR(129),CRI(129),XR(4),XI(4),FXR(4),FXI(4),SR(3),SC(3)
      READ 66, NOS, MODE
 66  FORMAT (I3,I1)
      DO 777 J=1, NCS
      ICOUNT = 0
      OCALL INPUT1 (CLALFA,EPIA,C,TL,XCG,XAC,ST,SW,CLALFAT,ETATAIL,SB,BL,
      1 RHO,G,W,EPSSALFA,THETA1,YH,CT,CMALFA,YI,V,CSUBD,CSUBL,KAPPA
      COMPUTATION OF STABILITY DERIVATIVES
      Q = .5 * RHO * V**2
      TCARAT = W / (G*RHO*V*SW)
      THETAC = THETA1 / 57.2957795
      XU = -CSUBL
      XW = .5*CSUBL*(1.0-(2.0*CLALFA/EPIA))
      ZW = -.5*(CLALFA + CSUBD)
      APRIME = .44 + 2.0*((XAC-XCG)/C)
      BPRIME = -.58 - CLALFA * APRIME * ((XAC-XCG)/C)
      WINGMC = 0.25 * ((C/TL)**2)*BPRIME
      TAILMC = -.50* CLALFAT * (ST/SW) * ETATAIL
      BODYMC = -0.01* (SB/SW)*((BL/TL)**2)
      TOTALMQ = WINGMC + TAILMC + BODYMC
      YIB = YI/((W/G)*TL**2)
      WINGZC = -.25*CLALFA*(C/TL)*(4.4+(XAC-XCG)*2.0/C)
      TAILZC = -.5*CLALFAT*(ST/SW)*ETATAIL
      U1 = W/(G*RHO*SW*TL)
      BARMWCT = -.5*CLALFAT*ETATAIL*(ST/SW)*EPSSALFA
      TOTALZQ = WINGZC + TAILZC
      ZU = -CSUBL
      XTHETA = -.5*CSUBL
      ZTHETA = -.5*CSUBL*TANF(THETAC)
      AMU = -CT * YH/TL
      AMW = .5 * CMALFA * C/TL
      PRINT 505, ST, SW, CLALFAT, ETATAIL, SB, BL, RHO, G, W, EPSSALFA, THETA1, YH,
      1 CT, CMALFA, YI
 5050 FORMAT (1H1/40H INPUT PARAMETERS //)
      111H TAIL AREA= F8.4,2X11H WING AREA= F9.4,2X,14H CL ALFA TAIL=
      2 F9.6,2X,1CH ETA TAIL= F9.6,2X,11H BCDY AREA= F9.2 /
      3 13H BCDD LENGTH= F8.5,2X,5H RHO= F10.7,2X,5H GEE= F8.5,2X,
      4 8H WEIGHT= F12.4,1X,3HLBS 2X,18H D EPSILCN/D ALFA= F9.6 /
      5 21H INITIAL PITCH ANGLE= F9.6,1X,7HGEGRES 2X,22H THRUST LINE DI
      6STANCE= F8.5,1X,4HFEET 2X,16H THRUST CCOEF CT= F8.6 /
      7 8H CMALFA= F9.6,2X,10H I SUB YY= F12.3,1X,15HSLUG FT SQUARED//)
      WRITE CLTPUT TAPE 5, 101
 101  FORMAT (/// 47H STABILITY DERIVATIVES //)
      WRITE OUTPUT TAPE 5, 105, V, TCARAT, Q
 105  FORMAT (19H FORWARD VELOCITY= F12.3,10H T CARAT= F10.6, 4H Q=
      1 F 14.4 /)
      WRITE CPUTPUT TAPE 5, 106, CSUBL, CSUBD
 106  FORMAT ( 9H C SUBL= F10.6, 9H C SUBD= F10.6 /)
      WRITE OUTPUT TAPE 5, 102, XU, XH, XQ, XTHETA, ZU, ZH, TCTALZC
 1020 FORMAT (5H XU= F7.4,6H XH= F7.5,6H XC= F7.4,10H XTHETA= F7.5,
      1 6H ZU= F7.5, 6H ZH= F7.4,12H TOTAL ZC= F7.4 /)
      WRITE OUTPUT TAPE 5, 103, ZTHETA, AMU, AMW, BARMWCT, TCTALMC, U1, YIB
 1030 FORMAT ( 9H ZTHETA= F7.4, 6H MU= F8.6, 6H MH= F7.5,14H MEAR W C
      1 6H MG= F7.4, 6H MUONE= F7.3,13H I SUB BETA= F7.4 /)
      OCALL PREROOT (XU, XW, XQ, XTHETA, ZU, ZW, TCTALZC, ZTHETA, AMU, AMW, BARMWCT
      1, TOTALMC, U1, YIB, TCARAT, A1, B1, C1, D1, E1, CRI, CRR
      ROUTH = CRR(2)* CRR(3)* CRR(4)- CRR(1)* CRR(4)**2-CRR(2)**2*CRR(5)
      WRITE OUTPUT TAPE 5, 108, ROUTH
 108  FORMAT (///35H THE VALUE OF ROUTH'S DESCRIPTOR = F10.2 )
      IF (RCUTH) 11, 11, 12
 11  WRITE OUTPUT TAPE 5, 109
 1C9  FORMAT (28H THE AIRCRAFT IS UNSTABLE //)
      GO TO 13
 12  WRITE OUTPUT TAPE 5, 110
 110 FORMAT (26H THE AIRCRAFT IS STABLE //)
 13  CONTINUE
      N = 4
      CALL POLYMUL (CRR, CRI, N, KAPPA, TCARAT)

```


C DECISION FCR LONG CR LATERAL, STICK FIXED(999), OR STICK FREE(2C1)
 GO TO (777,201,202,204),MCDE

2C1 CCNTINUE
 WRITE CLTPUT TAPE 5,301
 3010FORMAT(//// 80H STICK FREE LONGITUDINAL DYNAMIC STABILITY COEFF
 1 ICIENTS ////)
 WRITE OLTPUT TAPE 5, 302, KAPPA

302 FORMAT (1CA8)
 OCALL INPUT 2 (CTAIL,XKE,UE,B1,B2,B2PRIME,ZETA,ZETACDOT,AMETA,
 1 AMETADT)
 XKE = SCRTRF(XKE)
 ZQ = TCTALZQ
 AMQ = TOTALMQ
 OCALL PREROT2 (CTAIL,EPSSALFA,XKE,YIB,U1,UE,TL,B1,B2,B2PRIME,ZW,
 1 ZTHETA,ZQ,ZETA,ZETACDOT,AMW,AMQ,BARMWDT,AMETA,AMETADT,CRR,CRI)
 N = 5
 CALL FCLYMLUL (CRR,CRI,N,KAPPA,TCARAT)

777 CONTINUE
 END FILE 5
 STOP2

202 STOP4
 203 STOP5
 204 STOP6
 END

OSUBROUTINE INPUT1 (CLALFA,EPIA,C,TL,XCG,XAC,ST,SW,CLALFAT,ETATAIL,
 1 SB,BL,RHO,G,W,EPSSALFA,THETA1,YH,CT,CMALFA,YI,V,CSUBD,CSUBL,KAFEA)
 DIMENSION KAPPA(10),CPR(129),CPI(129),ROOTR(128),RCTI(128)
 DIMENSION CRR(129),CRI(129),XR(4),XI(4),FXR(4),FXI(4),SR(3),SI(3)
 READ 65, KAPPA

1C4 FORMAT (8F10.0)
 READ 104,ST,SW,CLALFAT,ETATAIL,SB,BL,RHO,G
 READ 1C4, W,EPSSALFA,THETA1,YH,CT,CMALFA,YI,V
 READ 104,CSUBD,CLALFA,EPIA,CSUBL,C,TL,XCG,XAC
 65 FORMAT (1CA8)
 RETURN
 END

SUBROUTINE PREROOT (XU,XW,XQ,XTHETA,ZU,ZW,TOTALZQ,ZTHETA,AMU,AMW,
 1 BARMWDT,TOTALMQ,U1,YIB,TCARAT,A1,B1,C1,D1,E1,CRI,CRR)
 DIMENSION KAPPA(10),CPR(129),CPI(129),ROOTR(128),RCTI(128)
 DIMENSION CRR(129),CRI(129),XR(4),XI(4),FXR(4),FXI(4),SR(3),SI(3)
 1 A1 = 1.0
 ZQMU = (1.0 +(TOTALZQ / U1))
 2 B1 = -(XU + ZW) - (TOTALMQ/YIB) - (ZQMU * BARMWDT/YIB)
 3 C1 = (XU * ZW - ZU) + (TCTALMQ/YIB) * (XU * ZW) + (XU * ZQMU - ZU *
 1 (XQ/U1) - ZTHETA) * (BARMWDT/YIB) - (U1 * AMW/YIB) * (ZQMU + XC/U1)
 4 D1 = -(TCTALMQ/YIB) * (XU * ZW - XW * ZU) + (-XTHETA * ZU + ZTHETA *
 1 XU) * (BARMWDT/YIB) + (U1 * AMW/YIB) * (XU * ZQMU - ZU * XC/U1 - ZTHETA) +
 2 (U1 * AMU/YIB) * (-XTHETA - XW * ZQMU + ZW * XQ/U1)
 5 E1 = (U1 * AMU/YIB) * (-XTHETA * ZU + ZTHETA * XU) - (U1 * AMU/YIB) * (-XTHETA *
 1 ZW + ZTHETA * XW)
 WRITE CLTPUT TAPE 5,101, A1,B1,C1,D1,E1

1C10FORMAT (/3H A= 1X,F13.5,4H B= 1X,F13.5, 4H C= 1X,F13.5, 4H D=
 1 1X,F13.5,4H E= 1X,F13.5 //)
 CRR(1) = A1
 CRR(2) = B1
 CRR(3) = C1
 CRR(4) = D1
 CRR(5) = E1
 CRI(1) = 0.0
 CRI(2) = C.C
 CRI(3) = C.C
 CRI(4) = 0.C
 CRI(5) = 0.0
 RETURN
 END

OSUBROUTINE INPUT2(CTAIL,XKE,UE,B1,B2,B2PRIME,ZETA,ZETACDOT,AMETA,
 1 AMETADT)
 SUBROUTINE BRINGS IN STICK FREE FACTORS
 0READ 1,CTAIL,XKE,UE,B1,B2,B2PRIME,ZETA,ZETACDOT,AMETA,AMETACDT,XKE,
 1 SE
 1 FORMAT (8F10.0 /4F10.0)

WRITE OUTPUT TAPE 5,2

20FORMAT(////10X7OH)

INPUT) PARAMETERS STICK FREE

END

SUBROUTINE PREROT2 (CTAIL, EPSALFA, XKE, YIB, U1, UE, TL, B1, B2, B2PRIME, Z
1h, ZTHETA, ZQ, ZETA, ZETACOT, AMW, AMQ, BARMWDT, AMETA, AMETACT, A, B
SUBROUTINE CALCULATES STABILITY STICK FREE QUINTIC COEFFICIENTS
CIMENSION A(129), B(129)
UFACTCR = 2.0 * UE / (U1**2)

UFACT = UFACTCR

FACTORK = (XKE / TL)**2

XKFACT = FACTORK

CTFACT = CTAIL / TL

ZFACT = (1.0 + (ZQ/U1))

EPSFACT = 1.0 - EPSALFA

WRITE OUTPUT TAPE 5,2001, UFACT, XKFACT, CTFACT, ZFACT, EPSFACT

2001FORMAT(49H FACTOR CALCULATIONS

1 9H UFACTOR= F14.7, 9H KFACTOR= F14.7, 1CH CTFACTCR= F14.7 //
210H ZCFACTCR= F14.7, 16H EPSALFA FACTCR= F14.7 //

A CCEFFICIENT CALCULATION

A(1)=UFACT * XKFACT * YIB

B CCEFFICIENT CALCULATION

0A(2)=UFACTOR * XKFACT * (BARMWDT * (ZETADCT * CTFACT / U1 - ZFACT) - AMQ - ZW *
1 YIB + AMETACT * CTFACT) - B2PRIME * CTFACT * YIB / U1

C CCEFFICIENT CALCULATION

CA(3)=UFACT * XKFACT * (ZW * AMQ + AMW * (ZETACOT * CTFACT - U1 * (ZFACT)
1) + EARMWDT * (ZETA - ZTHETA) + U1 * AMETA - AMETACT * CTFACT * ZW)
2 + B2PRIME * CTFACT / U1 * (AMQ + ZW * YIB + ZFACT * BARMWDT) - E2 *
3 YIB - B1 * (AMETACT * CTFACT / U1 + ZETADCT * CTFACT / U1 * (YIB * EPSFACT
4 + BARMWDT / U1))

D CCEFFICIENT CALCULATION

CA(4)=UFACTOR * XKFACT * (U1 * AMW * (ZETA - ZTHETA) - U1 * AMETA * ZW)
1 - B2PRIME * CTFACT / U1 * (ZW * AMQ - U1 * AMW * ZFACT - ZTHETA *
2 BARMWDT) + B2 * (AMQ + ZW * YIB + BARMWDT * ZFACT) - B1 * (AMETACT * CTFACT
3 * (EPSFACT * ZFACT - ZW / U1) + ZETADCT * CTFACT / U1 * (AMW - AMQ *
4 EPSFACT) + ZETA * (BARMWDT / U1 + EPSFACT * YIB) + AMETA)

E CCEFFICIENT CALCULATION

0A(5)=B2PRIME * CTFACT / U1 * U1 * AMW * ZTHETA + B2 * (ZTHETA * BARMWDT
1 T - ZW * AMQ + U1 * AMW * ZFACT) + B1 * (ZETA * (EPSFACT * AMQ -
2 AMW) + AMETA * (ZW - U1 * EPSFACT * ZFACT) - AMETACT * CTFACT *
3 EPSFACT * ZTHETA)

F CCEFFICIENT CALCULATION

0A(6)=U1 * ZTHETA * (B2 * AMW - AMETA * B1 * EPSFACT)

DO 100 J=1,129

100 B(J)=C.0

WRITE CPUTPUT TAPE 5,3,CTAIL, XKE, UE, B1, B2

3CFORMAT(/// 13H TAIL CHORD = F7.3,1X, 8HK SUB E= F9.5,1X,9FMU SUB
1E= F9.5,1X,8HB SUB 1= F9.5,1X, 8HB SUB 2= F9.5)

WRITE OUTPUT TAPE 5,4,B2PRIME,ZETA,ZETADCT,AMETA, AMETACT

4CFORMAT(/14H B SUB2 PRIME= F9.5,1X, 11H Z XUB ETA= F9.5,1X,
115H Z SUB ETA COT= F9.5,1X,11H M SYB ETA= F9.5,1X,16H M ISUB ETA

2 DOT= F9.5 //)

C1=UFACT * XKFACT * (U1 * AMW * (ZETA - ZTHETA) - U1 * AMETA * ZW)
C2=-B2PRIME / U1 * CTFACT * (ZW * AMQ - U1 * AMW * ZFACT - ZTHETA * BARMWDT)
C3=B2 * (AMQ + ZW * YIB + BARMWDT * ZFACT)
OD4=-B1 * (AMETACT * CTFACT * (EPSFACT * ZFACT - ZW / U1) + ZETADCT / U1 * CTFACT *
1 AMW - AMQ * EPSFACT) + ZETA * (BARMWDT / U1 + EPSFACT * YIB) + AMETA)
D=D1+D2+C3+D4

A(4)=C

60FORMAT(// 4H D1= F15.8, 4H D2= F15.8, 4H D3= F15.8, 4H D4= F15.8.

1 9H D TCTAL= F15.8, //)

E1=B2PRIME * CTFACT * (U1 * AMW * ZTHETA)

E2=B2 * (AMQ + ZW * YIB + BARMWDT * ZFACT - ZW * AMQ + U1 * AMW * ZFACT)

0E3=B1 * (ZETA * (EPSFACT * AMQ - AMW) + AMETA * (ZW - U1 * EPSFACT * ZFACT) -
1 AMETACT * CTFACT * EPSFACT * ZTHETA)

E=E1+E2+E3

70FORMAT(// 4H E1= F15.8, 4H E2= F15.8, 4H E3= F15.8, 9H E TCTAL=

1 F15.8, //)

OC1=UFACT * XKFACT * (ZW * AMQ + AMW * (ZETADCT * CTFACT - U1 * ZFACT) + BARMWDT
1 * (ZETA - ZTHETA) + U1 * AMETA - AMETACT * CTFACT * ZW)

C2=B2PRIME / U1 * CTFACT * (AMQ + ZW * YIB + ZFACT * BARMWDT)

QC3=-B2 * YIB - B1 * (AMETACT / U1 * CTFACT + ZETADCT / U1 * CTFACT * (YIB *
1))


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1 EPSFACT + BARMWCT/U1) )
C = C1 + C2 + C3
WRITE OUTPUT TAPE 5, 8, C1, C2, C3, C
WRITE OUTPUT TAPE 5, 6, D1, D2, D3, D4, D
WRITE OUTPUT TAPE 5, 7, E1, E2, E3, E
80FORMAT (/// 4H C1= F15.8, 4H C2= F15.8, 4H C3= F15.8, SH C TOTAL=
1 F15.8,           // )
RETURN
END
SUBROUTINE POLYMUL (CRR,CRI,N,KAPPA,TCARAT)
DIMENSION KAPPA(10), CPR(129), CPI(129), ROOTR(128), RCETI(126), SI(3)
DIMENSION CRR(129), CRI(129), XR(4), XI(4), FXR(4), FXI(4), SR(3), SI(3)
IMAX = 50
DEL = C.1
NUM = 5
RATIO = 5.0
ALTER = 1.COC001
EP1 = .CCCC0000000000CCCC00000001
EP2 = .COC000001
EP3 = .0CCCCGC1
EP4 = .0CCCCCC01
SR(1) = -.5
SI(1) = 0.0
SR(2) = C.5
SI(2) = 0.0
SR(3) = C.0
SI(3) = 0.0
MODE = 1
NNN = N+1
749 IF (CRR(1)) 750,751,750
751 CO 752 L=1,NNN
M = L+1
CRR(L) = CRR(M)
753 CONTINUE
752 N = N-1
GO TO 749
750 CONTINUE
65 FORMAT (1CA8)
DO 5 I=1,1C
KON=E
IF(KAPPA(I)-KON)2,5,2
5 CONTINUE
GO TC 999
2 PRINT 65,KAPPA
66 FORMAT(2X,2HN=I4,12X,5HIMAX=I3,10X,4HNUM=I3,11X,4HDEL=E8.2E
661 6X,6HRATIC=E8.2,4X,6HALTER=F10.8/
662 2X,4HEP1=E8.2,6X,4HEP2=E8.2,6X,4HEP3=E8.2,6X,4HEP4=E8.2/)
MODE=MODE+1
67 FORMAT(6H SR1= E12.5,6H SI1= E12.5,6H SR2= E12.5,6H SI2=
671 E12.5,6H SR3= E12.5,6H SI3= E12.5)
NP1=N+1
710FORMAT (46HCTHE COEFFICIENTS OF THE GIVEN POLYNOMIAL ARE    ///
1 11H REAL PART )
501 WRITE OUTPUT TAPE 5,71
6810FORMAT(11CH      A      B      C      D      E      /
1 F      G      H)
687 CONTINUE
WRITE OUTPUT TAPE 5, 680, (CRR(J),J=1,NP1)
680 FORMAT (1H 8F15.7 / )
WRITE OUTPUT TAPE 5, 682
682 FORMAT (16H IMAGINARY PART )
WRITE OUTPUT TAPE 5, 680, (CRI(J),J=1,NP1)
502 DO 6 I=1,NP1
CPR(I)=CRR(I)
6 CPI(I)=CRI(I)
CALL COMAG(CRR(1),CRI(1),C1,KE)
DO 3C5 K=1,N
GO TC(9,609),MODE
53 FORMAT(1H02X4HRCOT5X7HITERANT6X2(10HREAL PART1CX10HIMAG PART10X)
1,10HRCOT IS IN/2X6HNUMBER4X6HNUMBER7X2(SH CF ROOT11X),2(SH CF R(
2Z)11X),11HA RADIUS CF)
9 PRINT 53

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6C9   I=1
      NP1=N+2-K
      NN=NP1-1
11    IF(K+1-N)13,12,11
      CALL DIVD(-CRR(2),-CRI(2),CRR(1),CRI(1),XR(1)*XI(1),KE)
      K1=1
      K2=1
      GO TO 16
12    AR=CRR(1)
      AI=CRI(1)
      BR=CRR(2)
      BI=CRI(2)
      CR=CRR(3)
      CI=CRI(3)
      K1=1
      K2=1
      M4=2
      GOTO 123
14    XR(1)=CBARR
      XI(1)=CBARI
      GO TO 16
13    DO 15 J=1,3
      XR(J)=SR(J)
15    XI(J)=SI(J)
      K1=1
      K2=3
16    M1=1
      M2=1
      M3=1
      M4=1
700   DO 717 L=K1,K2
701   ZR=XR(L)
702   ZI=XI(L)
      CALL PCLYNCM(NP1,ZR,ZI,CRR,CRI,RR,RI,KE)
710   FXR(L)=RR
711   FXI(L)=RI
      CALL CCMAG(RR,RI,PMAG,KE)
713   RAD=ALTER*(PMAG/C1)**(1.0/FLOATF(NN))
714   GO TO (715,19,17$),M3
715   GO TO (716,718),MCDE
55    FORMAT(2(I6,4X),4E20.11,5X,E10.4)
716   PRINT 55,K,I,ZR,ZI,RR,RI,RAC
718   POLYC=PCLYN
      POLYN=PMAG
      IF(PMAG)717,300,717
717   I=I+1
      IF(K+1-N)17,300,300
17    GO TO (18,200),M1
18    VAL=DEL*PCLYN
      DBARR=RAD
      DBARI=0.0
19    K1=4
      K2=4
      M1=2
      M3=1
101   ABARR=XR(1)-XR(3)
102   ABARI=XI(1)-XI(3)
103   BBARR=XR(2)-XR(3)
104   BBARI=XI(2)-XI(3)
105   AMIBR=XR(1)-XR(2)
106   AMIBI=XI(1)-XI(2)
107   CALL MULT(ABARR,ABARI,BBARR,BBARI,TA,TB,KE1)
108   CALL MULT(TA,TB,AMIBR,AMIBI,DENR,DENI,KE2)
      CALL CCMAG(DENR,DENI,TA,KE)
      CALL CCMAG(XR(3),XI(3),T4,KE)
      IF(TA-EP1*T4)110,110,111
110   CALL DERIV(NP1,XR(3),XI(3),CRR,CRI,DR,DI,K50)
      CALL CCMAG(RR,RI,TR,KE)
      CALL COMAG(DR,DI,TD,KE)
      IF(TR-EP4*TD)192,171,171
111   DELAR=FXR(1)-FXR(3)
112   DELAI=FXI(1)-FXI(3)
113   DELBR=FXR(2)-FXR(3)

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114  DELBI=FXI(2)-FXI(3)
115  CALL MULT(EBARR,EBARI,DELAR,DELA1,TA,TB,KE5)
116  CALL MULT(ABARR,ABARI,DELBR,DELB1,TC,TD,KE6)
117  CALL CIVD(TA-TC,TE-TC,DENR,DENI,AR,AI,KE7)
118  CALL MULT(ABARR,ABARI,TC,TD,T1,T2,KE8)
119  CALL MULT(EBARR,EBARI,TA,TB,T3,T4,KE9)
120  CALL DIVD(T1-T3,T2-T4,DENR,DENI,BR,BI,KE10)
CR=FXR(2)
CI=FXI(3)
123  CALL MULT(ER,BI,ER,PI,T1,T2,KE11)
124  CALL MULT(AR,AI,CR,CI,T3,T4,KE12)
125  TA=T1-4.C*T3
126  TB=T2-4.O*T4
127  CALL CSQRT(TA,TB,TC,TD)
128  T1=-ER+TC
129  T2=-EI+TD
130  T3=-ER-TC
131  T4=-EI-TD
132  CALL CCMAG(T1,T2,TA,KE14)
133  CALL COMAG(T3,T4,TB,KE15)
134  IF(TA-TE)154,168,168
135  TA=TB
136  T1=T2
137  T2=T4
138  GO TC (157,159),M4
139  IF(TA)161,161,158
140  CALL COMAG(2.0*CR,2.0*CI,TB,KE16)
141  IF(TE-RAD*TA)159,159,18C
142  CALL DIVD(2.0*CR,2.0*CI,T1,T2,DBARR,DBARI,KE17)
143  GO TC (161,14),M4
144  XR(4)=XR(3)+CBARR
145  XI(4)=XI(3)+DBARI
146  TR=AESF(XR(4))
147  TI=AESF(XI(4))
148  IF(TR)167,167,14C
149  IF(TI)167,167,169
150  IF(TR-TI)164,167,163
151  IF(TI-EP2*TR)165,167,167
152  XI(4)=C.C
153  GO TC(5C3,504),MCDE
56  FORMAT(40HCITERANT ALTERED TO BE PURE REAL NUMBER.)
503 PRINT 56
504 GO TC 167
164 IF(TR-EP2*TI)166,167,167
166 XR(4)=0.0
167 GO TC(5C5,167),MCDE
57  FORMAT(45HCITERANT ALTERED TO BE PURE IMAGINARY NUMBER.)
505 PRINT 57
168 GO TC 7CC
169 CALL DIVD(T1,T2,TA ,C.O,T1,T2,K20)
170 CALL DIVD(CR,CI,TB ,C.O,CR,CI,K21)
171 CALL MULT(CR,CI,RAD,C.O,CR,CI,K22)
172 GO TC(5C6,507),MCDE
58  FORMAT(87H ITERANT IS OUTSIDE CIRCLE WHICH BOUNDS A ROOT.  INTERP
5810LATE ITERANT TO EDGE OF CIRCLE.)
506 PRINT 58
507 GO TC 159
173 CALL COMAG(ABARR,ABARI,T1,KR1)
    ENA(1) STA(ITA) ENA(3) STA(ITB)
174 IF(T1-EP3*T4)174,174,172
175 CALL COMAG(BBARR,BBARI,T2,KR2)
    ENA(2) STA(ITA) ENA(3) STA(ITB)
176 IF(T2-EP3*T4)175,175,173
177 CALL CCMAG(AMIBR,AMIBI,T3,KR3)
    ENA(1) STA(ITA) ENA(2) STA(ITB)
178 IF(T3-EP3*T4)174,174,171
    ENA(1) STA(K1) STA(K2) ENA(2) STA(M3) SLJ(178)
    ENA(2) STA(K1) STA(K2) ENA(3) STA(N3)
179 XR(K1)=XR(K1)*(1.0+2.0*EP3)
    XI(K1)=XI(K1)*(1.0+2.0*EP3)
180 GO TC(5C8,5C9),MCDE
60  FORMAT(11H0ITERANTS XI1,6H AND XI1,41H ARE TOO CLOSE TOGETHER ALT
181 1ER ITERANT X IT1,1H.)

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5C8 PRINT 6C,ITA,ITB,ITA
5C9 GO TC 7C0
179 POLY=C=PMAG
GO TC 19
2C0 IF(PCLYN-VAL)201,2C1,210
2C1 VAL=DEL*POLYN
2C2 LIM=I+NUM
203 M2=2
CALL DERIV(NP1,XR(4),XI(4),CRR,CRI,DR,DI,K60)
CALL CCMAG(RR,RI,TR,KE)
CALL COMAG(DR,DI,TC,KE)
IF(TR-EP4*TC)192,21C,21C
210 DLT=RATIO*POLY0/PCLYN
211 IF(1.0-DLT)22C,22C,212
212 CALL MULT(DBARR,DBARI,DLT,0.C,DBARR,DBARI,K3C)
215 LIM=LIM+1
GO TC (510,511),MCDE
72 FORMAT(120HOPCLYNOMIAL HAS INCREASED IN MAGNITUDE TOO MUCH WITH CU
72IRRENT STEP. THEREFORE REDUCE CURRENT STEP.)
510 PRINT 72
511 GO TC 161
220 GO TC (221,231),M2
221 IF(I-IMAX)250,250,222
222 PRINT 62
DO 684 J=1,NP1
684 CRR(J)=1C.C * CRR(J)
ICOUNT=ICOUNT+1
IF (ICOUNT-3) 685,685,777
685 WRITE OUTPUT TAPE 5,686
686 FORMAT(55HOTHE REVISED COEFFICIENTS OF THE GIVEN POLYNOMIAL ARE
1 //)
K=1
GO TO 687
62 FORMAT(69HOMAXIMUM NUMBER OF ITERATIONS REACHED WITHOUT REDUCING
621P(Z) BY DELTA.)
513 GO TC 777
777 RETURN
231 IF(I-LIM)250,250,300
250 DO 251 L=1,3
XR(L)=XR(L+1)
XI(L)=XI(L+1)
FXR(L)=FXR(L+1)
251 FXI(L)=FXI(L+1)
GO TC 1C1
192 GO TC (514,300),MCDE
69 FORMAT(19HOFIRST DERIVATIVE ( E17.9,E20.9,55H) INDICATES THAT THE
1RANT IS SUFFICIENTLY CLOSE TO ROOT.)
514 PRINT 69,DR,DI
300 DO 3C2 J=2,NN
CALL MULT(ZR,ZI,CRR(J-1),CRI(J-1),TR,TI,K4C)
CRR(J)=TR+CRR(J)
CRI(J)=TI+CRI(J)
302 CRI(J)=TI+CRI(J)
63 FORMAT(59HOTHE COEFFICIENTS OF THE REDUCED POLYNOMIAL ARE AS FOLLOWS )
631CWS )
ROOTR(K)=ZR
ROOTI(K)=ZI
GO TC (303,305),MCDE
303 PRINT 63
68 FORMAT(1H 6E18.9)
304 PRINT 68,(CRR(J),J=1,NN)
PRINT 68,(CRI(J),J=1,NN)
3C5 CONTINUE
GO TC (515,516),MCDE
515 PRINT 75
516 PRINT 8C
800FORMAT(1H042X14HTABLE OF ROOTS//3X4HRCCT8X 1CHREAL PART10X10HIMA
1G PART 10X 6HPERIOD 10X 26HTIME TO DAMP TO HALF AMPL
2 /2X6HNUMBER7X2(9H OF ROOT11X) )
DO 3C6 I=1,N
CALL PCLYNOM(N+1,ROOTR(I),RCOTI(I),CPR,CPI,RR,RI,KE)
THALF=-.69314718C6/ROOTR(I)*TCARAT
PERIOD=6.2831853C72/ABSF(ROOTI(I))+TCARAT
3C6 WRITE OUTPUT TAPE 5, 84, I, ROOTR(I),RCOTI(I),PERIOD,THALF

```



```

84 FORMAT (I6,4X,F16.6,3X,F16.6,7X,F10.4,8H SECS      5X,F10.4,5H SECS)
83 FORMAT(I6, 4X, 4E20.11)
75 PRINT 75
    IMAX = 50
    NUM = 5
    CEL = C.1
    RATIO = 5.C
    ALTER = 1.C0C001
    EP1 = .CCCCCCCC00000CCCCCCCC00001
    EP2 = .CCCC00001
    EP3 = .00000001
    EP4 = .0CC00001
    SR(1) = -5
    SI(1) = 0.0
    SR(2) = 0.5
    SI(2) = C.C
    SR(3) = 0.0
    SI(3) = 0.0
    MODE = 1
    GO TC 1
1 RETURN
CONTINUE
END
999 SUBROUTINE DERIV(N,ZR,ZI,CR,CI,DR,DI,KER)
DIMENSION CR(129),CI(129)
    ENA(C)      STA(DR)   STA(DI)   STA(RR)   STA(RI)ENA(1)STA(KER).
DO 2 J=1,N
    CALL MULT(ZR,ZI,RR,RI,TRR,TRI,K1)
    CALL MULT(ZR,ZI,CR,CI,TDR,TDI,K2)
        RSC(K1)  AJP1(L+2) RSC(K2)  AJP1(1)   ENA(2) STA(KER)SLJ(3).
1 DR=TCR+RR
    DI=TCI+RI
    RR=TRR+CR(J)
    RI=TRI+CI(J)
2 CONTINUE
END
SUBROUTINE PCLYNOM(N,ZR,ZI,CR,CI,RR,RI,KER)
DIMENSION CR(129),CI(129)
    ENA(0)      STA(RR)   STA(RI)   ENA(1)    STA(KER)
DO 2 J=1,N
    CALL MULT(ZR,ZI,RR,RI,TR,TRI,K1)
        RSC(K1)  AJP1(1)   ENA(2)    STA(KER)  SLJ(3)
1 RR=TR+CR(J)
2 RI=TRI+CI(J)
3 CONTINUE
END
SUBROUTINE CSCRT(XR,XI,YR,YI)
    CCN(SQ2=1.4142135624).
    LCA(XR)    LDQ(XI)   AJP2(L+1)  LAC(XR)   QJP2(L+1)  LCC(XI)
    STA(A)     STQ(B)    QJP1(1)    STQ(Q)    SLJ4(8)   +STA(P)SLJ(5).
1    AJP1(2)   LDA(B)    SLJ4(8)    +F0V(SC2)  STA(P)
2    SSK(XI)   SLJ(L+2)  LAC(P)    +STA(C)   SLJ(5)
3    THS(P)    SLJ(3)    STQ(S)    FCV(P)   STA(T)   STA(R)SLJ(4)
4    STA(S)    LDA(B)    FCV(A)   STA(T)    LCA(1.C)  STA(R)SLJ(4)
Y=SQRTF(X)
5    SLJ(*)    STA(X)    SLJ(7)    FAD(1.0)  SLJ4(8)   +FAD(R)   FCV(2:C)
4    LCA(T)    FMU(T)   FAD(1.0)  SLJ4(8)   +FMU(T)   STA(P)
6    SLJ4(8)  +STA(T)   LDA(S)   SLJ4(8)   +FAD(R)   FCV(2:C)
5    LCA(XI)   FCV(2:C)  FCV(P)   STA(C)   SLJ(5)
SSK(XR)   SLJ(6)    LDA(Q)   LCC(P)   AJP2(L+1)  LAC(C)
SSK(XI)   LDQ(P)    STA(YR)  STQ(YI)  SLJ(L+3)   :
LCA(P)    LDQ(Q)    STA(YR)  STQ(YI)   :
END
SUBROUTINE COMAG(XR,XI,Z,KER)
    LCA(XR)   LDQ(XI)   AJP2(L+1)  LAC(XR)   QJP2(L+1)  LCC(XI)
    STQ(T)    +THS(T)   LLS(48)   QJP(3)    STQ(T)   FCV(T)
    STA(H)    FMU(H)   FAD(1.0)  STA(H)    :
Y=SQRTF(H)
3    -FMU(T)  +EXF7(141B)SLJ(L+2) ENQ(1)   SLJ(3)   ENQ(2)
    STQ(KER)  STA(Z)   :
END
SUBROUTINE DIVC(XR,XI,YR,YI,ZR,ZI,KER)

```



```

CALL PRCO(XR,XI,YR,-YI,B1,B2,PR,PI,DR,DI)
LCA(B2) AJP1(1) ENA(3) SLJ(3)
2 EKA(2) SLJ(3)
T=DR+DR+DI*DI
LCA(B1) -FDV(B2) +EXF7(141B)SLJ(2) STA(B1)
LCA(PR) FDV(T) -FMU(B1) +EXF7(141B)SLJ(2) STA(ZR)
LCA(PI) FCV(T) -FMU(B1) +EXF7(141B)SLJ(2) STA(ZI)ENA(1)
3 STA(KER)
ENC
SUBRCUTINE MULT(XR,XI,YR,YI,ZR,ZI,KER)
CALL PRCO(XR,XI,YR,YI,B1,B2,PR,PI,DR,DI)
LCA(B2) -FMU(B1) +EXF7(141B)SLJ(1) STA(B1)
LCA(PR) -FMU(B1) +EXF7(141B)SLJ(1) STA(ZR)
LCA(PI) -FMU(B1) +EXF7(141B)SLJ(1) STA(ZI)
EKA(1) STA(KER) SLJ(L+2)
1 EKA(2) STA(KER)
ENC
SUBRCUTINE PROD(XR,XI,YR,YI,B1,B2,PR,PI,CR,DI)
CALL NORM(XR,XI,B1,AR,AI)
CALL NORM(YR,YI,B2,CR,DI)
PR=AR*CR-AI*DI
PI=AI*DR+AR*DI
END
SUBRCUTINE NORM(A1,A2,B1,S1,S2)
1A SLJ(1) +SEV7(70000E) ZRO(C) +ZRC(4000E)ZRC(C)
1 LDA(1A+1) LDQ(A1) CJP2(L+1) LQC(A1) STL(E) LDG(A2)
QJP2(L+1) LQC(A2) LCL(1A+1)+THS(E) SLJ(L+2) LDA(E)
+AJP1(L+2) STA(S1) STA(B1) SLJ(L+5) +ACC(1A+2) STA(B1)
LCA(A1) FDV(B1) STA(S1) LDA(A2) FDV(B1) +STA(S2)
END
END

```

CO31

	RUN	1	CG	26	V	224	FPS	F8U	1.29.63	BELL	NUMBERS	
93.4		375.0		2.393		1.0		288.5		52.8		002378
21000.0		4772		8.1		-437		0.195		-2937		52CC.C
195		2.759		9.3845		.902		11.78		14.08		29.625
F8U LONGITUDINAL RUN2 STICK FIXED M=.209, V=234 CG24, V=1.13 VSL												
93.4		375.0		2.393		.95		232.0		52.8		002378
22000.0		4772		5.6		-437		0.511		-380		560CC.C
19		2.59		9.3845		.90		11.78		14.08		29.375
RUN 3 C.C. 24, V=139 KTS, 234 FPS 3/3/63 LEVEL FLITE												
93.4		375.0		2.393		1.0		288.5		52.8		002378
22000.0		4772		8.1		-437		0.195		-380		560CC.C
263		2.920		9.3845		.90		11.78		14.08		29.375

APPENDIX III

SYSTEM MECHANIZATION FOR THE ANALOG COMPUTER

Fig. 1 to this Appendix displays the analog schematic for the equations of motion of the airframe. Fig. 2 includes the schematic for the System 1 auto-throttle, aircraft engine, and stick system dynamics simulations. Fig. 3 shows the System 2 auto-throttle schematic.

Table I lists the potentiometer settings for all systems.

Table II lists the scale factors used in computing these settings.

Table III describes the calculations used in arriving at these values.

Potentiometer Settings

Machine Input Variable	Pot Number	to Resistor	to Amplifier Number		Setting Syst. 1A	Setting Syst. 1B	Setting Syst. 2	
- α	1	1M	1		.056	.056	.056	
	2	1M	27		.408	.408		
- θ	3	1M	1		.013	.013	.013	
- θ	4	1M	1		.349	.349	.349	
+T	5	1M	1		.640	.640	.640	
+ α	6	.1M	30		.678	.678	.678	
+ α	7	.1M	30		.449	.449	.449	
+ θ	8	1M	30		.641	.641	.641	
-D θ	9	.1M	30		.998	.998	.998	
γ, δ_e	10	1M	30		.794	.794	.794	
+D θ	11	1M	2		.215	.215	.215	
+ α	12	.1M	2		.169	.169	.169	
+D α	13	1M	2		.061	.061	.061	
- α	14	1M	2		.014	.014	.014	
γ, δ_e	15	.1M	2		.260	.260	.260	
+T	16	1M	2		.517	.517	.517	
+D θ	17	1M	3		.312	.312	.312	
+D α	18	1M	4		.778	.778	.778	
-D θ	19	1M	26		.998	.998	.998	
	20				.500	.500	.500	
- Throttle Simulator	21	1M	5		.443	.443	.443	
- γ, δ_e	22	1M	29		.200	.200	.200	
+DT	23	1M	5		.874	.874	.874	
+ α	24	.025M	6		.600	.980		
	25	.1M	6		.500	.500		
	26	.1M	8		.618	.618	.182	
	27	.5M	12		.583	.583	.155	
	28	10K	12		.690	.115	.250	
	29	.5M	12		.856	.856	1.00	
	30	1M	9		.614	.614	.814	
γ, δ_e	31	.5M	15		.653	.653	.653	
+ α	32	.1M	10		.700	.145		
	33	.1M	11		.301	.301		
+D α	34	1M	26		1.000	1.000	1.000	
+ α	35	1M	26		.398	.398		
stick simulator	36	1M	20		$\approx .544$	$\approx .544$	$\approx .544$	

12ND NPS 95 (11-59) Appendix III Table I

Potentiometer Settings

Mechanic Input Variable	Pot Number	tu Resistor	tu Amplifier Number	Setting Syst. 1A	Setting Syst. 1B	Setting Syst. 2
-Spilot F	37	.5M	29	.192	.192	.192
-S _{d+c₁}	38	10K	6	.380	.380	.380
^{Voltage} _{ETC₃} limiter	39	.1M	27	.132	.132	.132
40	Diode			.330	.330	.330
-SF ₃	41	.1M	13	.571	.571	.571
+F ₁	42	.1M	13	.303	.303	.303
-F ₃	43	.1M	13	.598	.598	.598
-F ₃	44	.1M	15	.625	.625	.625
+ α	45	1M	23	.410	.410	.410
-100V	46	1M	24	1.00	1.00	1.00
-D θ	47	1M	21	0.350	0.350	.350
+D α	48	1M	21	.440	.440	.440

TABLE II
SCALE FACTORS USED IN ANALOG SIMULATION

Scale Factor	Value
α_o	.005 radians/volt = .286 degrees/volt
$\alpha_{\Delta\theta}$	.005 radians/volt = .286 degrees/volt
α_k	.002 radians/volt = .115 degrees/volt
$\alpha_{\Delta x}$	.005 radians/volt = .286 degrees/volt
α_u	.002V _o = .2% of V _o = .278 Kts/volt
α_{se}	.002 radians/volt = .115 degrees/volt
α_T	200 lbs/volt
α_{TC1}	40 lbs/radians - volt
α_{TC2}	50 lbs/kt - volt
α_{TC3}	120 lbs/radians - sec - volt
α_{DTC1}	210 lbs/radians - sec - volt
α_{DTC2}	30 lbs/radians - sec ² - volt
α_{DTC3}	300 lbs/radians - sec ² - volt
$\alpha_{\Delta v}$	2.5 kts/volt
α_{TCT}	100 lbs/volt for System 1, 50 lbs/volt for System 2
$\alpha_{TCPilot}$	50 lbs/volt
α_{F1}	2 lbs/volt
α_{F3}	.01 radians/volt
α_{DF3}	.1 lb/sec - volt
$\alpha_{Pilot F}$	.75 lbs/volt

$$\alpha_y = .286 \text{ degrees/volt}$$

$$\alpha_{ang} = .02 \text{ g/volt}$$

$$\alpha_{\frac{H}{V_0}} = .01 \text{ ft/ft/sec - volt}$$

Appendix III Table III

Potentiometer Setting Calculations

Potentiometer	Calculation	R value	$(C_f = 1 \mu F \text{ unless specified otherwise})$
1.	$X_u \frac{1}{\alpha_t} R C_f = -0.058$	1 M	
2.	$\frac{\alpha_{TC2}}{\alpha_{TC1}} R = .4$	1 M	
3.	$\frac{X_u \alpha_t}{\alpha_u \alpha_t} R = -0.01435$	1 M	
4.	$\frac{X_d \alpha_d}{\alpha_u \alpha_t} R = -0.3433$	1 M	
5.	$\frac{X_T \alpha_t}{\alpha_u \alpha_t} R = .6243$	1 M	
6.	$\frac{Z_w \alpha_d}{\alpha_{Dd}} \frac{R}{R_f} = -.556$	.1 M	$R_f = .1 M$
7.	$Z_u \frac{\alpha_u}{\alpha_{Dd}} R = -.36$	.1 M	
8.	$Z_d \frac{\alpha_d}{\alpha_{Dd}} R = -.641$	.1 M	
9.	$\left(\frac{z_g + 1}{\mu_i}\right) \frac{\alpha_{Dd}}{\alpha_{Dd}} R = .990$	.1 M	
10.	$Z_g \frac{\alpha_{se}}{\alpha_{Dd}} R = .780$	1 M	
11.	$\frac{m_g}{i_b} \frac{R C_f}{\alpha_t} = -.2139$	1 M	
12.	$\frac{m_w \alpha_d \alpha_t}{i_b} R = -.149$	.1 M	
13.	$\frac{m_w \alpha_d}{i_b} R = -.061$	1 M	
14.	$\frac{m_w \alpha_u}{i_b} R = .0149$	1 M	

Appendix III Table III continued

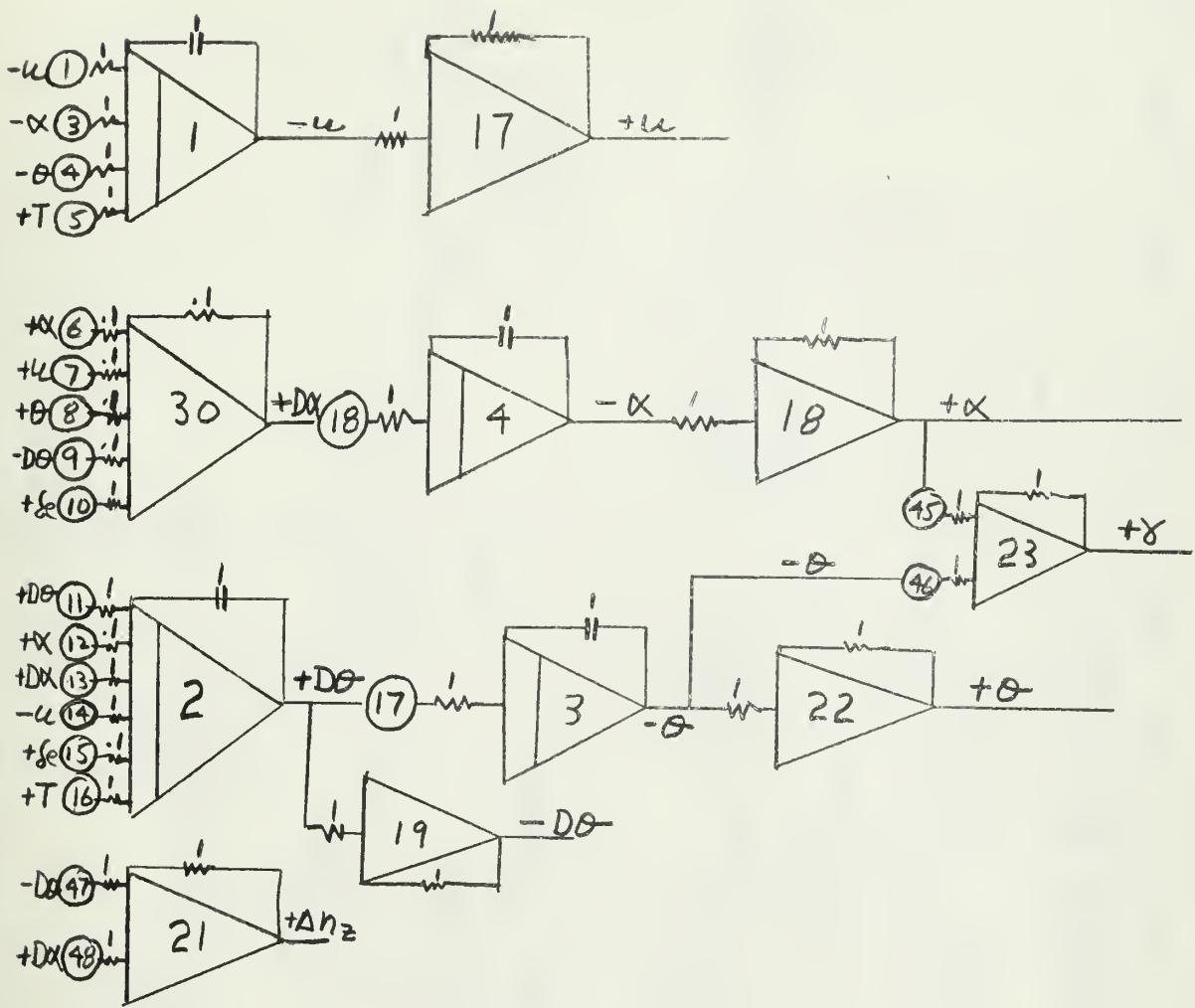
<u>Potentiometer</u>	<u>Calculation</u>	<u>R value</u>
15.	$\frac{m_2 \mu}{i_b} \frac{\alpha_{Se}}{\alpha_{D\alpha} \alpha_t} = -.3279$	.1 M
16.	$\frac{m_T}{i_b} \frac{\alpha_T \mu, R}{\alpha_{D\alpha} \alpha_t} = -.517$	.1 M
17.	$\frac{\alpha_{D\alpha}}{\alpha_t} R C_f = .3055$	.1 M
18.	$\frac{\alpha_{D\alpha}}{\alpha_t} R C_f = .764$	.1 M
19.	$\frac{K_{AV} \alpha_{D\alpha}}{\alpha_{AV}} \frac{R}{R_f} = .995$	.1 M $R_f = 1 M$
20.	$\frac{\alpha_{TC2}}{\alpha_{TC1}} R = .500$	.1 M
21.	$\frac{1}{T} \frac{\alpha_{TC1}}{\alpha_T} R C_f = .4316$	.1 M
22.	$\frac{\alpha_{PlatForce}}{\alpha_{F_1}} \frac{R}{R_f} = .200$	.1 M $R_f = 1 M$
23.	$\frac{R_f C_f}{1.16} = .862$	.1 M $R_f = 1 M$
24.	$\frac{K_R \alpha_R}{J_1 J_2 \alpha_{DTC1}} R = .6545$	.1 M
25.	$\frac{1}{J_1 J_2} \frac{\alpha_{TC1}}{\alpha_{DTC1}} R = .400$	.1 M
26.	$\frac{\alpha_{DTC1}}{\alpha_{TC1}} R = .500$	.1 M
27.	$\frac{J_1 + 1}{J_1} R C_f = .55$	.5 M $C_f = .1 \mu F$
28.	$\frac{K_V}{J_1} \frac{\alpha_{AV}}{\alpha_{DTC2}} R = .233$	10 K
29	$\frac{1}{J_1} \frac{\alpha_{TC2}}{\alpha_{DTC2}} R = .833$	.5 M

Appendix III Table III continued

<u>Potentiometer</u>	<u>Calculation</u>	<u>R value</u>
30.	$\frac{\alpha_{DTc2}}{\alpha_{TC2}} R = .600$	.1 M
31	$\frac{1}{\tau} R C_f = .625$	.5 M $C_f = .1 \mu F$
32.	$\frac{K_8 \alpha R}{\tau_1 \alpha_{DTc3}} = .145$	.1 M
33.	$\frac{\alpha_{DTc3} R}{\alpha_{TC3}} = .301$	.1 M
34.	$K_1 \frac{\alpha_{\Delta \alpha} R}{\alpha_{\Delta V} R_f} = .996$	.1 M $R_f = 1 M$
35.	$K_2 \frac{\alpha_{\Delta \alpha}}{\alpha_{\Delta V}} R = .388$	.1 M
36.	stick Trimmer = .508	
37.	$\frac{\alpha_{pilot Force}}{\alpha_{F1}} R = .1875$	.5 M
38.	$\frac{\tau_1 + \tau_2}{\tau_1 \tau_2} R = .120$	10 K
39.	$\frac{\alpha_{TC3}}{\alpha_{TCT}} R = .120$	.1 M
40.	Thrust limiter = .330	
41.	$\frac{b}{m} R = .490$	.1 M
42.	$\frac{K_1}{m} \frac{\alpha_{F1}}{\alpha_{DF3}} R C_f = .270$	.1 M $C_f = .1 \mu F$
43.	$\frac{K_2}{m} \frac{\alpha_{F3}}{\alpha_{DF3}} R = .515$	.1 M
44.	$\frac{1}{\tau} \frac{\alpha_{F3}}{\alpha_{de}} R = 625$	.1 M

Appendix III Table III concluded

<u>Potentiometer</u>	<u>Calculation</u>	<u>R value</u>
45.	$\frac{\alpha_x}{\alpha_y} R = .400$	1 M
47.	$K_{nZ} \frac{\alpha_{Dx}}{\alpha_{nZ}} R = .907$	1 M
48	$K_{nZ} \frac{1}{\epsilon} \frac{\alpha_{Dx}}{\alpha_{nZ}} R = .440$	1 M



Equations :

$$1. \left[\frac{d}{\dot{\epsilon} d \tau} - x_u \right] \frac{u}{v_0} - x_w \alpha - \left[x_o - \frac{x_g}{\mu_i} \frac{d}{\dot{\epsilon} d \tau} \right] \theta = x_r \Delta T$$

$$2. -z_u \frac{u}{v_0} + \left[\frac{d}{\dot{\epsilon} d \tau} - z_w \right] \alpha - \left[(1 + \frac{z_g}{\mu_i}) \frac{d}{\dot{\epsilon} d \tau} + z_o \right] \theta = (z_g + z_i) \eta$$

$$3. \left[-\frac{\mu_i m_u}{c_b} \right] \frac{u}{v_0} + \left[-\frac{m_w d}{c_b \dot{\epsilon} d \tau} - \frac{\mu_i m_w}{c_b} \right] \alpha + \left[\left(\frac{d}{\dot{\epsilon} d \tau} - \frac{m_g}{c_b} \right) \frac{d}{\dot{\epsilon} d \tau} \right] \theta = \left[\frac{\mu_i m_r}{c_b} \right] \eta + \left[\frac{\mu_i m_T}{c_b} \right] \Delta T$$

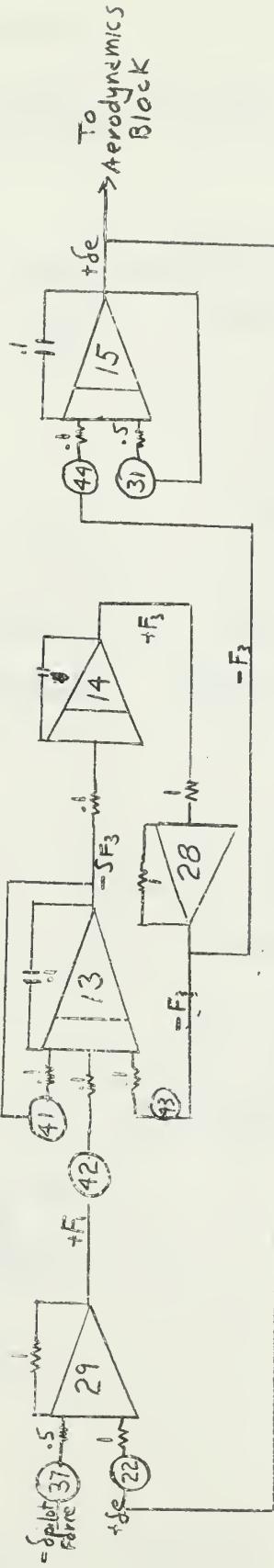
Appendix III Fig. 1

Analog Schematic, Airframe Equations of Motion

Analog Schematic, System 1 Auto-Throttle, Aircraft Engine, Stick System Dynamics

Appendix III Fig. 2

Stick System



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System 1 Auto-Throttle

System 1 Auto-Throttle Equations:

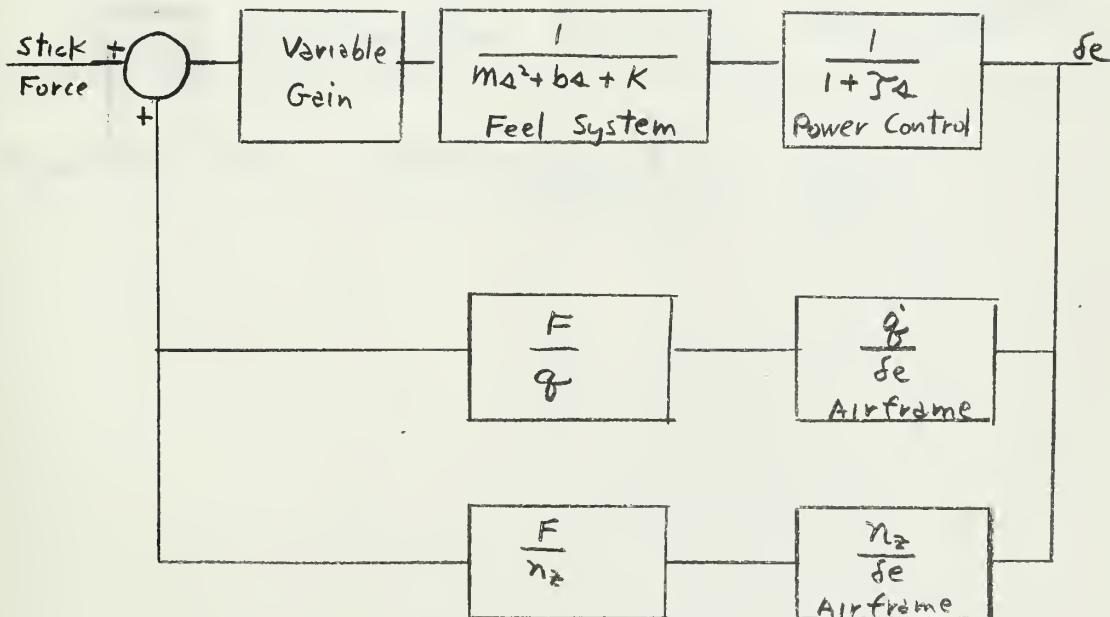
$$\Delta T = \frac{1}{1+.1A} \left[\frac{K_x \Delta X}{1+.5A} - \frac{K_{av} \Delta V}{1+A} + \frac{K_y \Delta \dot{X}}{A} \right]$$

where $\Delta V = (\Delta n_z - \frac{\Delta X}{X_0})$

Δn_z = change of normal acceleration, g's

X_0 = reference angle of attack

Longitudinal Control System Dynamics, Linearized



Variable Gain = $3^\circ \delta e / \text{inch stick}$

$m = .0388 \text{ lb. sec}^2 / \text{inch}$

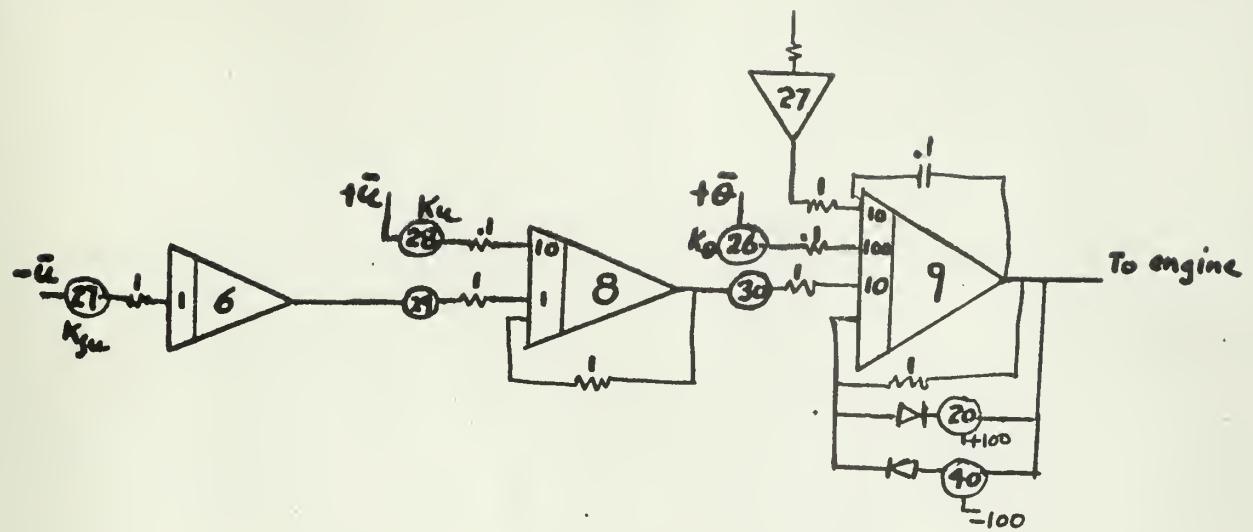
$b = 1.9 \text{ lb. / inch stick / sec}$

$K = 20 \text{ lb. / inch stick}$

$\tau = 1/12.5 \text{ sec}$

$\frac{F}{g} = 9.27 \text{ lbs/rad/sec}^2$

$\frac{F}{n_z} = 2.56 \text{ lbs/g}$



Analog Mechanization System 2 Auto-Throttle

$$\text{Equation: } \Delta T = K_\theta \Delta \theta - \frac{u}{(1+14)} \left[K_u + \frac{K_f u}{s} \right]$$

Appendix III Fig. 3



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An investigation of the effect of autoth



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